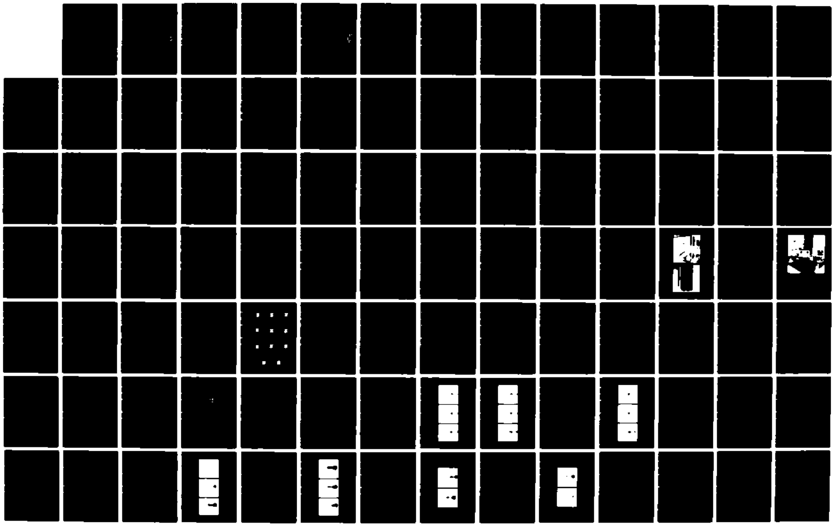
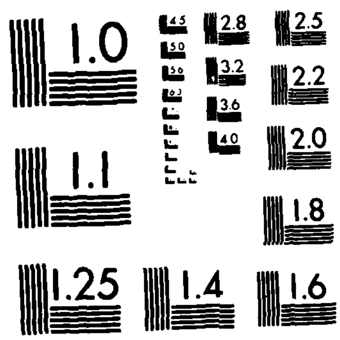
AD-A145 376 DIAGNOSTICS OF IONIZATION IN AIR PRODUCED BY INFRARED RADIATION FROM A PULSE CO2 LASER(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH E S HUTTON 1984 1/2

UNCLASSIFIED AFIT/CI/NR-84-64T F/G 20/5 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

UNCLASS

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

AD-A145 376

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER AFIT/CI/NR 84-64T	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Diagnostics Of Ionization In Air Produced By Infrared Radiation From A Pulse CO_2 Laser	5. TYPE OF REPORT & PERIOD COVERED THESIS/DISSERTATION
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Edward S. Huston	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS AFIT STUDENT AT: Creighton University	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS AFIT/NR WPAFB OH 45433	12. REPORT DATE 1984
	13. NUMBER OF PAGES 87
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) UNCLASS
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

DTIC ELECTE SEP 13 1984 S D

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

B

18. SUPPLEMENTARY NOTES

APPROVED FOR PUBLIC RELEASE: IAW AFR 190-1

Lynn Wolaver

LYNN E. WOLAVER
Dean for Research and Professional Development
AFIT, Wright-Patterson AFB OH

5 Sept 84

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

ATTACHED

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASS

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

DTIC FILE COPY

84 09 13 030

ABSTRACT

This thesis begins with a brief account of the historical development of the modern concept of the atom and, building on this foundation, the physical principles responsible for the operation of a LASER are presented. A more detailed description is then given of the pulsed CO_2 LASER used in this research, including principles of operation and safety procedures. Next, the research itself is described: an analysis of the ionization in air produced by focusing the LASER's infrared radiation. The data are ~~is~~ summarized in graphs which map the region of ionization. Following conclusions on the research performed, specific suggestions are made for future work with the LASER.

AFIT RESEARCH ASSESSMENT

The purpose of this questionnaire is to ascertain the value and/or contribution of research accomplished by students or faculty of the Air Force Institute of Technology (AU). It would be greatly appreciated if you would complete the following questionnaire and return it to:

AFIT/NR
Wright-Patterson AFB OH 45433

RESEARCH TITLE: Diagnostics Of Ionization In Air Produced By Infrared Radiation From A Pulse CO_2 Laser

AUTHOR: Edward S. Huston

RESEARCH ASSESSMENT QUESTIONS:

1. Did this research contribute to a current Air Force project?

( ) a. YES ( ) b. NO

2. Do you believe this research topic is significant enough that it would have been researched (or contracted) by your organization or another agency if AFIT had not?

( ) a. YES ( ) b. NO

3. The benefits of AFIT research can often be expressed by the equivalent value that your agency achieved/received by virtue of AFIT performing the research. Can you estimate what this research would have cost if it had been accomplished under contract or if it had been done in-house in terms of manpower and/or dollars?

( ) a. MAN-YEARS ______ ( ) b. $______

4. Often it is not possible to attach equivalent dollar values to research, although the results of the research may, in fact, be important. Whether or not you were able to establish an equivalent value for this research (3. above), what is your estimate of its significance?

( ) a. HIGHLY SIGNIFICANT ( ) b. SIGNIFICANT ( ) c. SLIGHTLY SIGNIFICANT ( ) d. OF NO SIGNIFICANCE

5. AFIT welcomes any further comments you may have on the above questions, or any additional details concerning the current application, future potential, or other value of this research. Please use the bottom part of this questionnaire for your statement(s).

NAME GRADE POSITION

ORGANIZATION LOCATION

STATEMENT(s):

FOLD DOWN ON OUTSIDE - SEAL WITH TAPE

AFIT/NR
WRIGHT-PATTERSON AFB OH 45433

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE. $300

NO POSTAGE
NECESSARY
IF MAILED
IN THE
UNITED STATES

BUSINESS REPLY MAIL
FIRST CLASS PERMIT NO. 73236 WASHINGTON D.C.

POSTAGE WILL BE PAID BY ADDRESSEE

AFIT/ DAA
Wright-Patterson AFB OH 45433

FOLD IN

Thesis Approved

By

Major Advisor

Dean

DIAGNOSTICS OF IONIZATION IN AIR
PRODUCED BY INFRARED RADIATION FROM
A PULSED CO_2 LASER

BY

EDWARD S. HUSTON, Major, USAF

A THESIS

Submitted to the Faculty of the Graduate School of Creighton University in Partial Fulfillment of the Requirements for the Degree of Master of Science in the Department of Physics

Omaha, 1984

ABSTRACT

This thesis begins with a brief account of the historical development of the modern concept of the atom and, building on this foundation, the physical principles responsible for the operation of a LASER are presented. A more detailed description is then given of the pulsed CO_2 LASER used in this research, including principles of operation and safety procedures. Next, the research itself is described: an analysis of the ionization in air produced by focusing the LASER's infrared radiation. The data is summarized in graphs which map the region of ionization. Following conclusions on the research performed, specific suggestions are made for future work with the LASER.

ACKNOWLEDGEMENTS

My thanks to the Air Force Institute of Technology counselors who encouraged me to write this thesis and to the Air Force Manpower and Personnel Center which permitted me to attend school full time this summer. My sincere thanks for the technical advice, insightful suggestions, and friendship of Dr. Thomas H. Zepf. His active support provided the motivation that kept this research going. I express my deepest thanks to my wife, Lou Ann, for her acceptance of the long hours this degree kept me from her and for her encouragement and confidence in me. I dedicate this thesis to her. I also thank our parents, Dot and Bill and Irma and Al, whose constant encouragement and pride in us made the going a whole lot easier.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT)

LIST OF FIGURES

LIST OF FIGURES (CONT)

CHAPTER I

PHYSICS OF LASER OPERATION

I.1 Purpose

This chapter is included for two reasons. First, it presents the basic physical concepts and principles behind LASER operation for those unfamiliar with them. Second, it provides a common conceptual and language base for those who already have a working knowledge of LASER principles. In either case, it is hoped that familiarity with the material in this chapter will give the reader a fresh appreciation of LASER physics.

I.2 The Atom

An understanding of the operation of LASERs must begin with a model of the atom. One of the first models leading to our present concepts was offered by Thomson in 1904. He suggested that the atom was a sphere of uniform positive charge in which negatively charged electrons were embedded. He believed that the electrons, as they revolved about the sphere's center along fixed rings, emitted light in accordance with the laws of electrodynamics.

Rutherford, by 1911, had added some additional concepts to the model of the atom. Through experimentation, he discovered that the positive charge of the atom occupied only a very small part of the atom's volume, the 'nucleus'. While he correctly identified the hydrogen nucleus as consisting of a proton, he believed that the nucleii of heavier elements were composed of both protons and electrons, to satisfy both the mass and charge measurements he had made. Other electrons, he claimed, circled this nucleus, leaving most of the volume of the atom as

nothing more than empty space.

By 1913, Bohr had modified Rutherford's model of the atom in several significant ways. (dA 51, pp. 490-491) Bohr made four basic claims. First, he proposed that an electron could travel only in certain permissible orbits around the nucleus, i.e., circles of quantized energies. Second, he claimed that no radiation was emitted when an electron traveled in an allowed orbit since this was a stable state for the atom. Third, he suggested that radiation was emitted from an atom when an electron changed from one orbit to another of lower energy; the atom would expel the energy difference in the form of radiation. He offered the converse of this event to explain radiative absorption. And fourth, he postulated that the frequency of emitted radiation was the energy difference between the electron's initial and final orbits, divided by Planck's constant.

Sommerfeld later proposed that the orbits of electrons were not stable circles, but precessing ellipses. This increased the number of energy levels in which the electrons could exist, and thus increased the number of possible transitions causing radiation. Zeeman's experiments with atoms in a magnetic field revealed that the sublevels of energy associated with the precessing ellipses were further divided by the presence of a magnetic field into sub-sublevels, increasing the number of possible transitions. Lande's analysis of atomic spectra led Uhlenbeck and Goudsmit to the suggestion of still another factor affecting electron transition: electron spin. The resulting magnetic moment within the atom explained additional energy sublevels that had been observed.

I.3 Quantum Numbers

To this point, most conclusions about atomic structure had resulted from experiment. De Broglie had tried unsuccessfully to explain the fine points of the experimental conclusions mathematically. Also attempting to represent the atom mathematically, Schroedinger, rather than pursuing a DeBroglie wave solution, began with the d'Alembert wave equation. (dA 51, p. 688) His solution contained three parameters, which have come to be known as quantum numbers, whose functions in the wave equation tie them to the electron orbit size, orbit precession, and orbit rotation in a magnetic field, as identified in the experiments mentioned above. The parameters were given the following designations and found to have the following ranges of values:

PARAMETER	DESIGNATION	VALUES
Electron Orbit Size	n	1,2,3,...
Orbit Angular Momentum	l	0,1,2,...,n-1
Magnetic Angular Momentum	m	-l,...,-1,0,1,...,l

The fourth quantum number, related to electron spin, was designated s and allowed to have the values +1/2 and -1/2, indicating the direction of electron spin. Each electron in an atom is fully described by this set of four quantum numbers. In the absence of a magnetic field, electrons with the same values for n and l have the same total energy. The distinction between such electrons provided by different values of m and s only becomes apparent in the presence of a magnetic field. Because of this, the energy states filled by such electrons are called 'degenerate energy states'; the presence of a magnetic field 'lifts' the degeneracy.

Further, Pauli found that no two electrons within an atom will have the same set of four quantum numbers. This is known as the Pauli Exclusion Principle.

I.4 Transitions

Study of the spectra of atoms had revealed that some emission lines were brighter than others, indicating that some of the electron energy transitions were occurring more frequently than others. Transitions which occurred frequently, indicated by bright spectral lines, were labeled 'allowed transitions', while those which occurred relatively infrequently were labeled 'forbidden transitions'. Because the ground state of an atom is stable, no spontaneous transitions from this state occur. On the other hand, spontaneous transitions from excited states are normally expected. It was found that there existed some excited energy levels from which all transitions were, surprisingly, forbidden. These levels were labeled 'metastable levels', and the corresponding states of the atom 'metastable states'. Typically, an electron will remain in an excited state for only a microsecond, to several powers of 10 less, before it drops to a lower energy level through an allowed transition. However, an electron may remain in a metastable state for a millisecond, to several powers of 10 more, before transitioning to a lower level by means of a forbidden transition.

Selection rules have been identified which allow predictions to be made concerning the forbiddenness of a transition:

(1) The quantum number l must change by plus or minus 1 during a transition.

(2) The quantum number m can change by plus or minus 1, or not

change at all, during a transition. If m is 0 before a transition, it will be +1 after the transition.

(3) The sum of the quantum number s values cannot change during a transition. Thus, the number of electrons changing their spin from +1/2 to -1/2 must equal the number changing their spin from -1/2 to +1/2. When an odd number of electrons is involved, the odd electron is prohibited from changing its spin direction.

While the initial support for the selection rules concerning the l and m numbers came from spectral analysis, the same conclusions are reached through solutions of the Schroedinger wave equation. Notice that there is no selection rule limiting the transitions between quantum number n values.

I.5 Radiation Emission and Absorption

As mentioned above, Bohr discovered that the frequency of radiation emitted or absorbed during an atomic state transition was equal to the difference in electron energy levels divided by Planck's constant. Work in the area of radiation emission and absorption was furthered by Einstein, who developed formulas for the rates of atomic transitions. (Ei 17, pp. 121-128) He determined that the rate of spontaneous emission, R(se), was simply the number of atoms in a given excited state, N(1), times the reciprocal of the lifetime of the transition, A(10)=1/t. This reciprocal is known as the 'Einstein coefficient of spontaneous emission'.

$$R(se)=N(1)A(10) \tag{I.1}$$

He also determined that the rate of stimulated absorption of radiation

by atoms, R(sa), was the number of atoms in an unexcited state, N(0), times the spectral density of radiation energy at the frequency of transition, ρ, times a constant of proportionality, B(01). This constant is known as the 'Einstein coefficient of stimulated absorption'.

$$R(sa)=N(0)\rho B(01) \tag{I.2}$$

The absorption of radiation expressed in (I.2) is called 'positive absorption'. A second kind of absorption, called 'negative absorption', had been identified. Negative absorption is actually an emission of radiation, stimulated emission. Stimulated emission can occur when an atom in an excited state encounters a photon of energy equal to that of the difference between the excited state and a lower energy state of the atom. Einstein correctly specified that the rate of stimulated absorption must equal the rate of stimulated emission for a system in equilibrium. That is, B(01)=B(10). Corroborating Planck's radiation law, Einstein showed that the ratio of the probability of spontaneous emission to that of stimulated emission, A(10)/B(10), was:

$$A(10)/B(10)=8\pi\nu^3 h/c^3 \tag{I.3}$$

where ν is the frequency of radiation created in the transition between excited and unexcited states of the atom. It is clear from this equation that stimulated emissions are far less frequent than spontaneous emissions, a fact that becomes a significant factor in LASER operation. One of the challenges of LASER development was to 'hold' enough atoms in their excited state, preventing their spontaneous (random) emission, until stimulated emission could release the energy in a controlled manner. Thus, the last three letters of the acronym LASER: 'S'timulated 'E'mission of 'R'adiation.

Another significant characteristic of stimulated emission, discovered later, led directly to development of the LASER. The stimulated emission of radiation resulting from an atomic transition is in phase with the radiation which stimulated the transition. As a result, the stimulated radiation adds constructively to the stimulating radiation, increasing its amplitude. This characteristic accounts for the remaining letters in the acronym: 'L'ight 'A'mplification.

I.6 Atomic Populations

Population refers to the number of atoms existing in any given energy state at a particular time. Consider a collection of atoms existing at some temperature T. The energy resulting from random atomic collisions maintains some of the atoms in excited states. When the system is at equilibrium, the atomic population in the ground and each excited state will be constant in time. From his work in kinetic theory, Boltzmann discovered that the ratio of populations between any two energy states was dependent only on the energy difference of the states and the temperature of the system. (Bo 68) The ratio of the population of one energy state, N(b), to that of some lower state, N(a), is:

$$N(b)/N(a)=e^{-E/kT} \tag{I.4}$$

where E is the energy difference between the states and k is Boltzmann's constant. Where several energy states are possible for the atoms of interest, the populations are related as shown in Figure I-1.

At a temperature of 300 degrees absolute, room temperature, nearly all atoms of a gas are in its ground state. This is determined from the fact that the absorption lines of gases at this temperature are

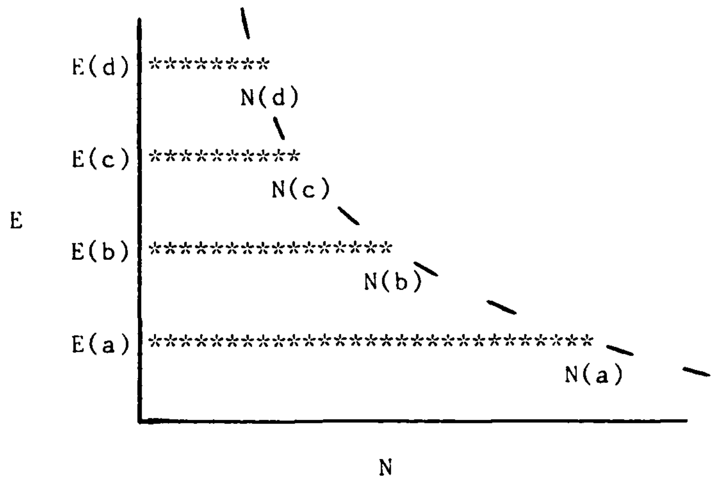


Figure I-1. Normal Boltzmann Population.

predominantly of transitions from the ground state to higher states. When the temperature of these same gases is raised to several thousand degrees, the higher energy states are far more populated than previously. This is indicated by the appearance of absorption lines of transitions between the higher states.

I.7 Atomic Pumping

It was mentioned previously that stimulated emission results in the constructive addition of light energy. To produce noticeable LASER outputs, sufficient quantities of atoms must be involved in this constructive process. Specifically, a system must be constrained to have a larger number of atoms in a particular excited state than exist in some lower state to which the atoms will transition. This non-equilibrium condition is called a 'population inversion'. The energy stored in this population inversion is the source of energy which is output by a LASER.

For a large number of atoms to exist in a high energy state, relative to a lower state, they must be 'pumped' by some means to the higher state. Several means of pumping atoms have been discovered. Atoms

may be excited by 'optical pumping', in which the necessary energy is derived from incident photons. Excitation may also be caused by 'mechanical pumping', in which the energy is derived from atomic or molecular collisions.

How to maintain an atomic population inversion was one of the major problems in the development of the LASER. Even though pumping may populate a higher energy state, that state would normally depopulate itself spontaneously (randomly) before the atoms could be stimulated to release their energy in a constructive manner. And while high temperature operation increases the proportion of atoms in the higher energy states, this will never create a population inversion. The problem of maintaining a population inversion is that the condition that causes population of the higher states is the very cause of their immediate depopulation.

In 1956, a solution to the problem was proposed by Bloembergen. (Bl 56, pp. 324-327) His solution demanded that several criteria be satisfied:

(1) The type of atom to be stimulated have at least three distinct energy levels, call them 0, 1, and 2.

(2) The transition from level 0 to level 2 be one which can be stimulated by some means of pumping.

(3) The transition from level 2 to level 1 be 'allowed' (rapid).

(4) The transition from level 1 to level 0 be 'forbidden' (slow).

Pumping atoms that meet these criteria, from level 0 to level 2, will result in the population configuration identified in Figure 1-2. Notice

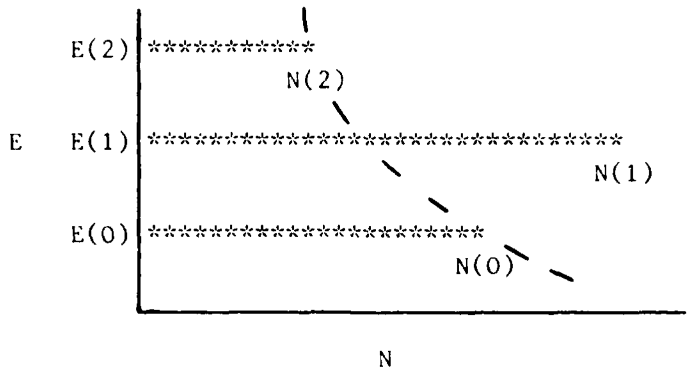


Figure I-2.

that while the relative population of E(1) has increased, the ratio N(2)/N(0) still obeys the Boltzmann relationship in (I.4).

I.8 Lasing

Once an inverted population is achieved, a condition must be created by which the excess atoms in E(1) are transitioned to E(0) through stimulated emissions before they can return to E(0) by spontaneous emissions. Spontaneous emissions from E(1) to E(0), which occur randomly, will themselves stimulate additional in-phase emissions. The result of this action occurring naturally will be the existence of many groups of constructively added photons of energy. These groups, however, will not be in phase with one another because they were each initiated by random spontaneous emissions.

A further constraint is needed which will maximize the number of emitted photons constructively added to one another. The solution to this problem consists of placing the collection of atoms within a 'LASER cavity'. Such a cavity has two reflective surfaces opposite one another which are designed to efficiently reflect photons of the frequency created in the atomic transition from E(1) to E(0). The photons are reflected back and forth through the cavity many times, rather than

being allowed to escape within one pass. This leads to a 'chain reaction' of stimulated emissions, all resulting from one spontaneous emission. The effect, which is far greater than the one described in the previous paragraph, is called 'lasing'.

A final condition must be met for the energy produced in lasing to be useful. One of the reflective surfaces must be partially transmissive at the lasing frequency so that a portion of the created energy can exit the cavity and be used to perform the desired task.

Application of the above principles led to construction of the first pulsed LASER, in 1960, by T. H. Maiman at the Hughes Aircraft Corporation Research Laboratories. The active medium used in this LASER was a pink ruby crystal. (Ma 60, pp. 493-494) The first continuous wave LASER was constructed later in 1960 by A. Javan at the Bell Telephone Laboratories using a mixture of helium and neon gas as the active medium. (Ja 61, pp. 106-110)

1.9 Q-switching

Since lasing efficiently produces high power outputs, it is understandable that attempts have been made to modify LASERs to produce greater power. Because the output of lasing is dependent on the quantity of atoms 'held' in an excited state, methods which increase the population inversion will create higher power outputs.

Time is required to invert atomic populations. If lasing can be delayed after the start of atomic pumping, more extreme inversions can be created. Then, once lasing begins, the avalanche of stimulated emissions will be far more powerful and rapid. Thus, LASERs which are 'pulsed' can achieve greater power outputs than 'continuous wave' LASERs, given that other design features are comparable.

The scientific variable which relates energy storage to energy dissipation is the 'quality factor', Q. It is defined as:

$$\frac{2\pi \times \text{energy stored}}{\text{energy dissipated per cycle}}$$

Thus, a high Q value for a LASER would imply lasing is not occurring at a significant rate, whereas a low Q value would imply intense lasing. Compared to electrical storage devices with Q values of several hundred, the LASER cavity is a far better storage device with Q values of 10^5 or 10^6. Changing conditions within the LASER cavity to initiate the avalanche discussed above is called 'Q-switching'.

Several methods are used for rapid Q-switching. The first three examples are considered 'active Q-switches'; the fourth is a 'passive Q-switch'. (OS 77, pp. 114-120)

(1) One of the reflecting surfaces of the LASER cavity may be mechanically rotated. Once it and the second surface are aligned such that the photons are repeatedly reflected, lasing occurs.

(2) An electro-optic crystal may be used to interrupt the reflection of photons within the LASER cavity. When voltage is not applied to the crystal, radiation passes through it undisturbed. Once voltage is applied, the plane of polarization of the radiation passing through the crystal is rotated 90 degrees. When the crystal is used in conjunction with a polarizer, passage of photons, and therefore lasing, is controlled by the presence or absence of voltage on the crystal.

(3) An acoustooptic modulator may be used in a fashion similar to the electrooptic crystal. As long as sound waves are applied to the modulator, which is located within the LASER cavity, radiation passing through it is scattered, preventing lasing. When the waves are terminated, lasing initiates.

(4) Dyes which absorb radiation at the lasing frequency can be placed in the LASER cavity along with the lasing material. When the atomic pumping begins, the dye absorbs the random spontaneous emissions of the lasing material. This effectively eliminates any stimulated emissions and allows a greater population inversion of the lasing material than would occur if the dye were not present. When the excited states of the dye atoms are full, stimulated emissions become possible, and lasing occurs.

CHAPTER II

THE CARBON DIOXIDE LASER

II.1 Development

The first LASER emissions from carbon dioxide (CO_2), which occur in the infrared portion of the electromagnetic spectrum, were reported by Patel in 1964. (Pa 64, p. 588) Very shortly afterward, Legay and Legay-Sommaire discovered that the lasing efficiencies of Patel's pure CO_2 system could be improved by stimulating CO_2 molecules with excited nitrogen molecules (N_2). (Le 64, p. 99) Since N_2 is easily excited by electrical discharges, this offered a convenient method for CO_2 stimulation. Growing interest in the CO_2 LASER led quickly to the discovery that the addition of helium (He) to the CO_2 and N_2 mix permitted greater power output. By the end of 1965, power output by CO_2 LASERs had increased from approximately a milliwatt to roughly a hundred watts. The CO_2 LASER had made a dramatic debut as an efficient convertor of electrical power to infrared radiation. In 1969, Beaulieu discovered that the CO_2 LASER could operate at pressures near and above atmospheric. (Be 70, p. 504) This led to the design of CO_2 LASERs with extremely short pulse durations and extremely high energy outputs. The success of these efforts, and the usefulness of the CO_2 LASER output, gave the system a bright and solid future.

II.2 The Gases

II.2.A. Molecular Energy States

In monatomic gases, energy levels depend on the movements of the atom's electrons. These movements establish the atom's electronic states. Chapter 1 discusses these states. When diatomic, or larger,

molecules are considered, vibrational and rotational states must be considered in addition to the electronic ones. The vibrational and rotational states are defined by the movements of the atoms of a molecule relative to one another. In the operation of the CO_2 LASER, the vibrational states are far more important than the rotational or electronic states. For this reason, vibrational states will be the only ones considered in the following discussion.

II.2.B. Carbon Dioxide

As its title would indicate, the carbon dioxide LASER depends primarily on the characteristics of carbon dioxide for its operation. The high efficiencies achievable in the CO_2 LASER are a result of two characteristics of CO_2 molecules. First, the lower energy level to which the CO_2 molecule transitions when lasing is relatively close to the ground state of the molecule. The energy difference between the energy state after lasing and the ground state is approximately one-sixth of an electron-volt (eV) for the CO_2 molecule, compared to nearly 17 eV's for the lasing gases in helium-neon and argon LASERs. Hence, energy losses due to transition to the ground state are minimized. Second, CO_2 molecules are easily excited vibrationally. The resulting high efficiencies range from 15 to 20 percent, compared to most other LASER efficiencies which are measured in tenths of a percent.

The high power output possible from a CO_2 LASER, beyond that attainable in any other LASER system, is due to the availability of a great number of excited states in the CO_2 molecule and the molecule's ability to be 'cooled' during lasing. These factors are discussed below. Furthermore, the specific power of each CO_2 LASER system is dependent on

the gas mixture, cavity size, and discharge current used.

There are over 200 possible CO_2 lasing transitions which produce photons between 8 and 18 micrometers (μm). The primary transitions are due to the transitions between the CO_2 molecule vibrating with one quanta of asymmetric stretching (the 001 mode) to either one quanta of symmetric stretching (100 mode) or two quanta of bending (020 mode). Light emitted by the first of these transitions has a wavelength of 10.6 μm; light emitted by the second has a wavelength of 9.6 μm. The stretching modes involve motions along the straight line joining the three atoms. The asymmetric stretching mode occurs when the two oxygen atoms move in the same direction while the carbon atom moves in the opposite direction; the symmetric stretching mode occurs when the oxygen atoms move in opposite directions to one another while the carbon atom does not move at all. The bending mode occurs when the oxygen atoms move in a direction opposite that of the carbon atom's movement so as to cause a 'bend' in the line joining the atoms. (While two degenerate bending modes can occur, in two perpendicular planes passing through the line joining the atoms, they will be treated as one mode in this discussion.) See Figure II-1.

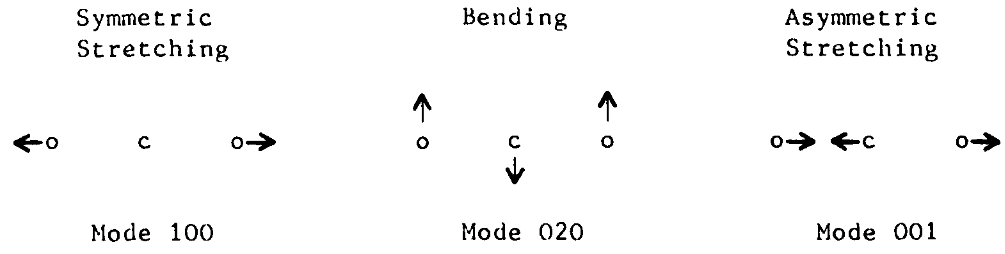


Figure II-1. Carbon Dioxide Molecular Modes.

Decay of the 100 and 020 modes to the 010 (single quanta of bending) are allowed (fast) transitions. Decay of the 010 to the 000 (non-vibrating) mode is a forbidden (slow) transition. Also, transitions of all vibrational modes between 002 and 004 to the 001 mode are allowed. The importance of this will become apparent below.

In addition to collisions with N_2 molecules, to be discussed shortly, CO_2 molecules also experience collisions with low-energy electrons. Because 000 to 001 is an allowed transition, whereas 000 to 100 or 020 are not, the CO_2-electron collisions preferentially populate the upper CO_2 energy level. (Ha 74, pp. 84-85; Sv 76, pp. 209-212; Ve 81, pp. 269-279)

II.2.C. Nitrogen

The primary contribution of the nitrogen molecules is to excite the CO_2 molecules into the upper level of their lasing transition through mechanical collisions. The N_2 molecules are easily excited to their vibrational (stretching) modes by a strong electric discharge. The energy of the lowest of these modes (n=1) matches the energy of the CO_2 001 mode within approximately two-thousandths of an eV, easily close enough to result in a highly efficient energy transfer from the N_2 to CO_2 molecules. See Figure II-2.

The N_2 molecules may also be excited into higher stretching modes, two through eight quanta (n=2...8). One of the transition selection rules which applies to homonuclear molecules such as N_2 is that optical (radiative) transitions between its vibrational modes are forbidden. This means that the only way the upper energy levels of the N_2 molecules can be depopulated is through collisions. Thus, these higher energy N_2

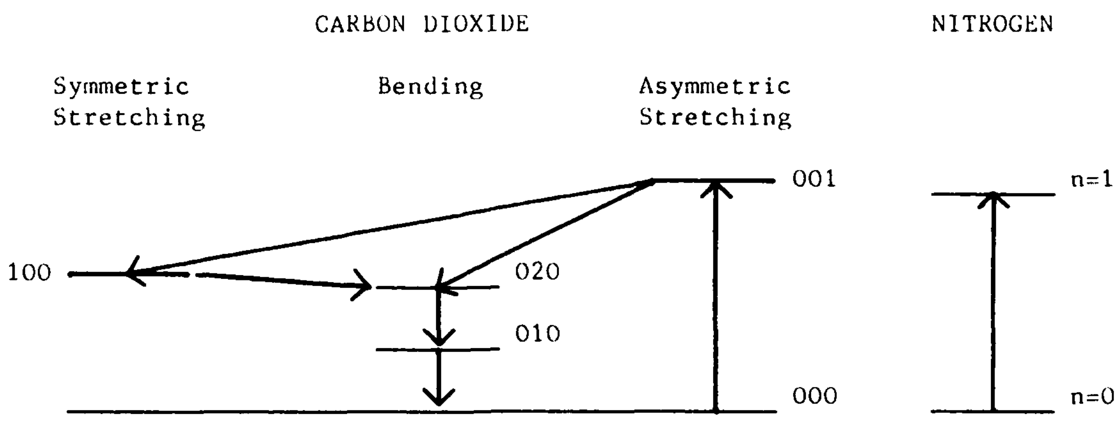


Figure II-2. Molecular Energy Levels.

molecules must maintain their energy until colliding with CO_2 molecules. Since, as mentioned above, the CO_2 002 through 004 modes transition rapidly to 001, at least some of the higher N_2 modes also aid in producing the CO_2 population inversion. (Ve 81, p. 278)

II.2.D. Helium

It was mentioned above that the transition from the CO_2 010 mode to the 000 mode is forbidden. However, the rate of this transition is drastically increased in the presence of helium. As a result, the 010 mode can be depopulated rapidly enough to prevent it from limiting the number of higher energy transitions, and thus the amount of lasing, which can occur.

Helium's high thermal conductivity also keeps the CO_2 gas 'cold' by conducting heat within the cavity to the walls. Keeping the CO_2 gas cold prevents its molecules from repopulating the lower energy levels (100, 020) as a result of thermal excitation. This effect, along with that in the previous paragraph, increases both the lasing efficiency and the power output of the CO_2 LASER. (Sv 76, pp. 212-213)

II.2.E. Mixture Ratios

The optimum mixture of CO_2, N_2, and He is determined empirically for each particular LASER system. A good initial ratio is 0.8:1:7, respectively. Then, maintaining the $CO_2:N_2$ ratio at 0.8:1, the $[CO_2:N_2]:[He]$ ratio should be varied until optimum LASER output is obtained. Finally, the $CO_2:N_2$ ratio should be 'fined-tuned' for optimum performance. (Du 76, pp. 16-17)

II.3 Gain Switching

Gain is normally defined as the ratio of two powers. In the case of a LASER it is generally the ratio of beam power before and after some length of travel within the LASER cavity; e.g., 'round-trip power gain'. The gain necessary to just overcome losses within a LASER and maintain a steady state output is called the 'threshold gain'. Gain is increased when the population inversion of the lasing gas is increased. Gain is decreased when spontaneous emissions decrease the population inversion.

The description of lasing given in paragraphs I.7, I.8, and I.9 indicated the requirement for at least three distinct energy levels within the lasing material, with the population inversion developing in the middle level. The CO_2 LASER is an exception to this in that the population inversion develops in the highest level (CO_2 001 mode in Figure II-2). This unusual behavior is possible for two reasons. First, the CO_2 molecules are excited by mechanical collisions rather than by radiative absorption which would also work to depopulate the upper level. And second, the rate of spontaneous emission by the CO_2 molecules in the upper level is extremely slow, on the order of 0.3 emissions per second.

The rate at which the CO_2 molecules are excited to their upper energy level through collisions with the N_2 molecules, approximately the kinetic collision rate, is on the order of 10^8 to 10^9 per second. Because this rate is significantly higher than the rate at which spontaneous emissions depopulate the upper level, the population inversion initially builds up faster than the beam intensity within the LASER cavity. By the time the beam, produced by stimulated emission, reaches an intensity which destroys the population inversion, a tremendous gain has developed within the cavity. A short, powerful pulse of energy is the result. This effect is called 'gain-switching'. In the gain-switched LASER, the value of Q is high from the outset. It is the establishment of high gain, occurring just as the intensity of the radiation is growing rapidly, which produces the powerful output. (Du 76, pp. 68-69; OS 77, pp. 70-71; Ve 81, pp. 212-213)

II.4 Specifications

The CO_2 LASER used in this work is the Lasermark System, model 901, manufactured by Lumonics Inc. of Ontario, Canada. It was obtained in 1983 by Creighton's Physics Department through the Control Data Corporation Capital Equipment Grant Program. The system was used by Control Data to etch identification numbers on computer memory disks. The following is provided as a quick reference to key specifications of the LASER. (Lu 81, pp. 1-3, 1-6, 2-9, 3-5)

PARAMETER	VALUE
Safety Category	Class IV (Bureau of Radiological Health), indicating potential to cause skin burns or eye damage
Voltage hazard	50,000 volts (when cover removed)
Output energy	5 joules
Output wavelength	10.6 micrometers
Output pulse duration	0.1-20 microseconds
Input voltage	115 volts, 60 Hz
Input power	350 watts (max)
Operating temperature conditions	40-100 degrees F (5-38 C)
Operating humidity conditions	10-90 % relative
Operating rate	90 shots per minute (max 120/minute for up to 10 seconds)
Dry air supply input pressure	30 psig (in 1/4 inch tube)
Cavity gas mixture	
CO_2	6, 8, or 10 % (8 % recommended -- 7.83 % used)
N_2	6, 8, or 10 % (8 % recommended -- 7.76 % used)
He	Balance of mixture (84.41 % used)
Input pressure	30 psig (in 1/4 inch tube)

II.5 Schematic

Figure II-3 is a schematic of the high-voltage electrical circuitry of the Lasermark System. The following is a key to the coded components in that figure.

COMPONENT	CODE
High voltage power supply	A
Spark gap high-voltage electrode	B
Spark gap mid-plane	C
Spark gap ground electrode	D
Discharge capacitor	E
Mid-plane blocking capacitor	F
Charging resistor	G
Pre-ionization capacitors (28)	H
Spark plugs (14)	I
Cavity high-voltage electrode	J
Cavity ground electrode	K
Remote control panel	L

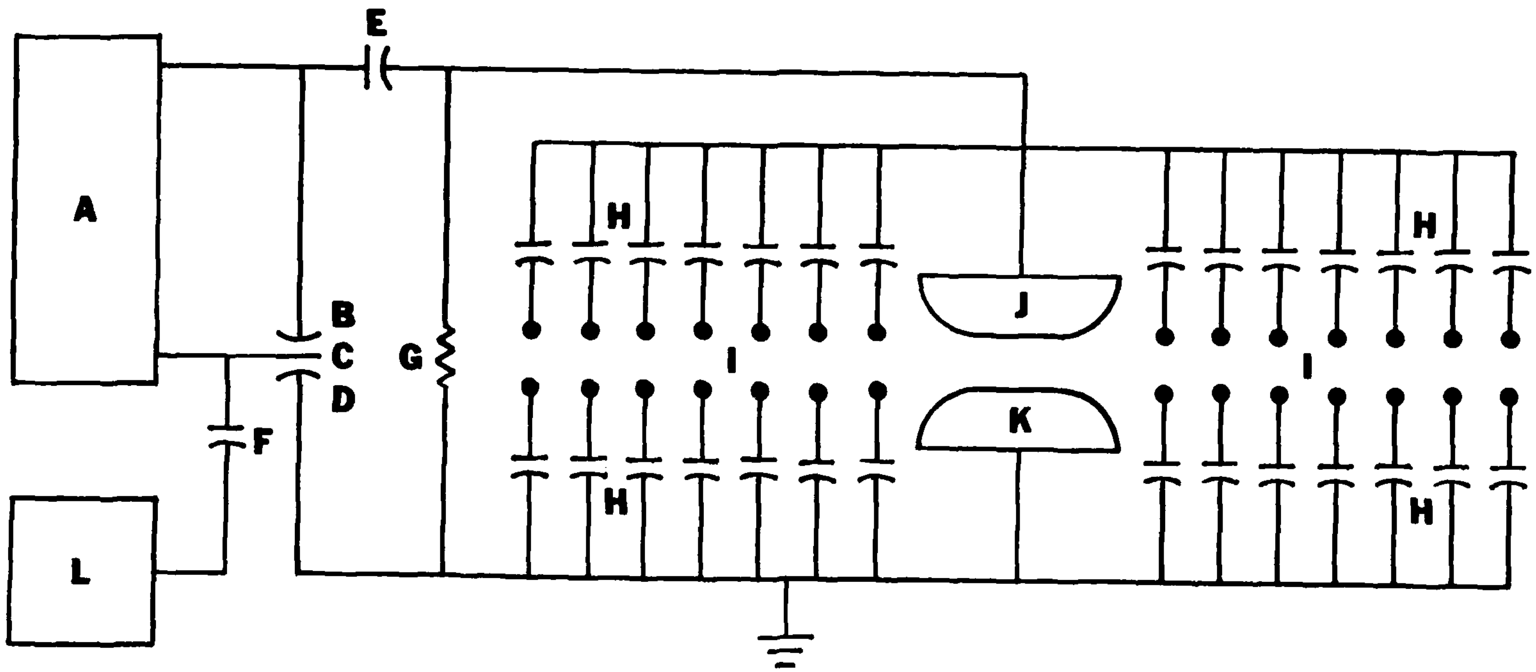


Figure II-3. High-Voltage Electrical Circuitry Schematic.

Figure II-4 is a schematic of the gas subsystem of the Lasermark System. The following is a key to the coded components in that figure.

Dry air bottle	A
Mix gas bottle	B
LASER dry air flow control	C
LASER mix gas flow control	D
Spark gap	E
LASER cavity	F
Dry air vent	G
Mix gas vent	H

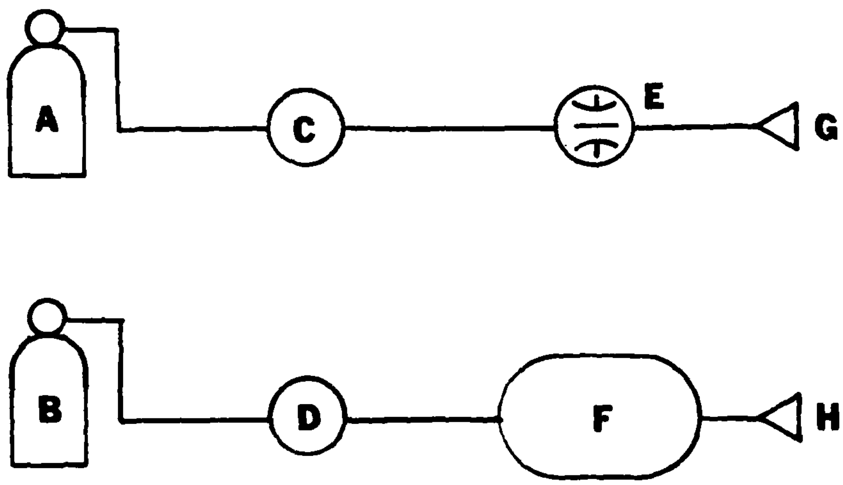


Figure II-4. Gas Subsystem Schematic.

II.6 Electrical Sequences

II.6.A. Charging Sequence

Voltage is applied to the spark gap by the high voltage power supply. This is accomplished when keyswitches on the Remote Control Panel are turned to the 'Operate' and 'Manual On' positions, specifically the 'Manual On' position. The spark gap high-voltage electrode, and therefore the high voltage terminal of the main discharge capacitor, is raised to a potential of 36 kV. The spark gap mid-plane is raised to a potential of 18 kV, thus maintaining a uniform field across the entire spark gap.

In addition to the above, two other important conditions are established when the keyswitches are turned on: the mix gas is allowed to flow and the circuit of the trigger transformer is energized.

II.6.B. Firing Sequence

The firing sequence is initiated by depressing the 'Single Shot Test Pushbutton', found on the inside of the Remote Control Panel cover. This pushbutton activates the trigger transformer, which applies 50 kV to the spark gap mid-plane, sufficient to cause the spark gap to break down. As a result, the high-voltage electrode of the spark gap and the high-voltage side of the main discharge capacitor suddenly drop to ground potential. At the same time, the other side of the main discharge capacitor, which was originally at ground potential, drops by the same amount to a potential of -36 kV.

This -36 kV potential is applied to the copper stripline which connects the pre-ionization capacitors on one side of the spark plugs and the cavity high-voltage electrode. As a result, the 14 spark plugs

fire. The light given off by the spark plugs is rich in ultra-violet radiation, which ionizes some of the molecules of the mix gas within the LASER cavity. When this so-called 'pre-ionization' occurs, the resistance of the mix gas decreases. The potential difference between the cavity high-voltage and ground electrodes is now sufficient to cause a uniform electrical discharge in the mix gas.

The discharge excites the N_2 molecules into their various stretching modes. As described previously, the N_2 molecules then transfer their energy to the CO_2 molecules, which in turn produce the LASER radiation. Because the electrical discharge occurs perpendicular to the optical axis of the cavity, and because the LASER operates at pressures near atmospheric, the LASER is identified as a Transversely Excited Atmospheric Pressure (TEA) LASER.

II.7 Operating the LASER

II.7.A. Safe Operation

Safety must be a paramount consideration during all phases of operating the LASER. As a Bureau of Radiological Health Class IV device, the beam from this LASER has the potential to cause skin burns and eye damage. In addition, the high voltage present in the circuitry of this LASER adds electrocution to the list of health hazards. Appendix 1 covers specific procedures which will contribute to safe operation, and all users of the LASER should be familiar with Appendix 1 before following the steps outlined in the present section.

II.7.B. Controls and Indicators

The controls and indicators which are important in operating the LASER are located on either the main cabinet front panel or the remote

control panel. A brief description of each control or indicator located on these panels is found in Appendix 2. If further explanation of the effect or use of controls, or of the information provided by indicators, is needed, the user should refer to the system Operator's Instruction Manual.

II.7.C. Operating Procedures

II.7.C.(1) Safing the LASER

This procedure is covered first because it should be followed regardless of previous use or status of the LASER. Safing the LASER should be accomplished any time the main cabinet cover is removed. This includes removal for simple operations, such as checking the power supply oil level or realigning the output mirror, as well as for more extensive operations, such as component removal. All users of the LASER should assume that every activity in or around the LASER while the cover is removed is hazardous until the LASER is methodically safed.

Safing the LASER involves removing all external power and properly grounding high-voltage terminals within the main cabinet. Detailed steps for safing the LASER are found in the 'Safing the LASER' checklist of Appendix 3.

II.7.C.(2) Turning On the LASER

The LASER is prepared for operation by activating the electrical and gas subsystems. The gas subsystem is activated by applying a line pressure to the dry air and mix gas input ports on the front panel of the main cabinet. This is normally accomplished by merely opening the control valves on the top of each gas supply bottle. The electrical subsystem is then activated by supplying low AC voltage to the LASER,

followed by establishing a voltage across the Spark Gap by energizing the high-voltage circuitry within the LASER. The former is accomplished by turning the Main AC Power Switch on; the latter is accomplished by turning the Mode Selector Switches to Operate and Manual On. Detailed steps for turning on the LASER, including gas flow and pressure adjustments, are found in items 1 through 12 of the checklist entitled 'Firing the LASER' found in Appendix 3.

II.7.C.(3) Firing the LASER

Once the high-voltage circuitry has been charged, the only 'trigger' necessary to result in firing the LASER is to break down the spark gap. This event is initiated by one push of the Single Shot Test Pushbutton. Pushing this button is the final step in the 'Firing the LASER' checklist found in Appendix 3.

II.7.C.(4) Turning Off the LASER

For reasons of safety and conservation, the LASER should be turned off when it will not be fired for an extended period and any time qualified personnel are not able to monitor its use. Detailed steps for turning off the LASER are found in the checklist entitled 'Shutting Down LASER' found in Appendix 3.

II.7.D. Maintenance

A thorough description of Preventative Maintenance, Malfunction Troubleshooting, Adjustments, and Replacement of Parts is found in Chapter 3 of the system Operator's Instruction Manual.

II.8 Some Major Uses of CO_2 LASERs

Like all other LASERs, the CO_2 LASER is a controllable and highly directional source of heat. That characteristic makes it a valuable tool

for all processes in which the heating of materials plays an important role. While the LASER's role in the processing of solids is its most important, the effect of its radiation on liquids and gases has been extensively studied because of their creation during the heating of solids. Because of the high powers achievable with the CO_2 LASER, it is a leader in processes requiring large amounts of heat. (Du 76, pp. 201-205)

Drilling is one of the processes performed by the CO_2 LASER. LASER drilling does not require the replacement of conventional bits, can drill higher aspect ratio (depth to diameter) holes and smaller holes, and can be done on extremely hard materials. Characteristics which affect the drilling of materials are the power delivery capabilities of the LASER, the rate at which heat is absorbed by the material, the melting and vaporization temperatures, the amount of energy reflected away from the surface by material ejected as a result of heating, and the presence of impurities.

Welding is another major use of the CO_2 LASER. An advantage of the LASER over an arc welder is that it causes less heat damage to the area surrounding the weld, resulting from the shorter time involved in heating. This allows the LASER to be effectively used for welding small and fragile parts.

CO_2 LASERs are also used to cut materials. As expected, as the speed of cutting is increased, the area affected by the LASER becomes narrower. Beyond the 'critical speed' the molten material is not completely removed and the cut becomes jagged.

The accuracy and intense heat of the CO_2 LASER also make it

suitable for use as a surgical tool. The intense heat provides instant cauterization of the LASER-produced incision, minimizing blood loss and promoting healing of the wound. CO_2 LASERs have been used for operations on the brain and vocal cords, for tumor removal, and for the joining of tissues. They may also prove to be useful for the drilling of teeth.

CHAPTER III

BEAM SETUP

III.1 LASER Activation

As the Lasermark System, Model 901, LASER was still in its shipping condition, the first responsibility in using the LASER was to get it into an operating configuration. It was decided that Rigge Science Building room L20 would be a convenient, secure, and safe place to operate the LASER. After it was moved to that room, a visual inspection was made of observable cabinets and components. No discrepancies were found. The level of the power supply oil reservoir was also checked, and was adequately full. A satisfactory ground was located and the LASER main cabinet properly grounded. As dry air and mix gas supplies had been ordered and delivered, the cylinders were connected to the LASER and the line pressures properly adjusted. The LASER was finally plugged into a standard 110 V, 60 Hz, wall receptacle and the Main AC Power Keyswitch turned on. The LASER properly responded to the power and timed in.

Next, the high-voltage circuitry was energized and an attempt was made to fire the LASER. The pulse of emitted radiation was expected to be beyond the visible, in the infrared, portion of the spectrum with a duration of only a few millionths of a second. Because of this, heat-sensitive paper, which would change color when irradiated by the beam, had been acquired and placed in front of the beam exit opening of the main cabinet. Since the full effect of the beam was yet unknown, a brick beam catcher that had been built to absorb excess energy was placed directly behind the paper. Because the LASER did not appear to fire on the first attempt, the malfunction portion of the Operator's Instruction

Manual was consulted. As indicated by the manual, the LASER power was cycled off and on several times to allow the mix gas to adequately purge the cavity of atmospheric gases. The first successful firing of the LASER, as determined by the discoloration of the heat-sensitive paper, occurred at 7:09 PM on April 10, 1984.

III.2 Beam Alignment

Once the LASER was consistently firing properly, the beam-directing mirror was adjusted to align the beam horizontal to the floor and perpendicular to the side of the main cabinet where the beam exited. In addition to the heat-sensitive paper, a reuseable sheet of heat-sensitive liquid crystal had been acquired. This sheet was used to determine the location of the beam for the alignment procedure. Once the position of the beam had been determined, the LASER was turned off, safed via the 'Safing the LASER' checklist, a small azimuth or elevation adjustment made to the mirror, the LASER turned on, and the new location of the beam determined. This was obviously a slow and painstaking procedure.

After several iterations of the above steps had been performed, a simpler, faster alignment method was discovered. The mirror and the cavity lens are highly reflective to visible light. An observer sees his own image when he looks into the beam exit opening of the main cabinet, the image formed by light reflected from the mirror to the cavity lens back to the mirror and out the opening. This configuration makes it possible to align the mirror by determining the desired beam direction, placing one's eye at some distance from the LASER along that direction, and adjusting the mirror until an image of the eye is seen at the center

of the mirror, all done with the LASER completely off and safe, of course.

III.3 Beam-Focusing Lens Focal Point Determination

As the beam exits the main cabinet, it is relatively broad (approximately one inch square) and of low irradiance (power per area). To effectively do the kind of tasks it was designed for, the beam must be focused to a high irradiance. This is done by a separate germanium lens, which is positioned in the beam somewhere external to the main cabinet. This lens is held in a tube which protects the lens and makes its positioning more convenient.

In order to determine its focal length, a number of shots were fired through the lens. The beam shape was recorded, at increasing distances from the lens, on the heat-sensitive paper. While there is some slight spreading of the beam over a distance of several meters from the main cabinet, all measurements were taken with the lens not more than half a meter away. Beam spreading over this distance is insignificant for the data taken. As expected, the effects on the paper were increasingly dramatic. A verbal description of the effect of the beam at each position is found in Appendix 4 and the image formed on the heat-sensitive paper at each position is found in Appendix 5. The first entry in both appendices is for the unfocused beam, used as a reference.

The data from Appendix 4 is plotted in Figure III-1, Vertical Image Size vs. Distance from Lens. Extrapolating the plot to the horizontal axis provided a first estimate of the focal point; i.e., 102 mm from the center of the lens.

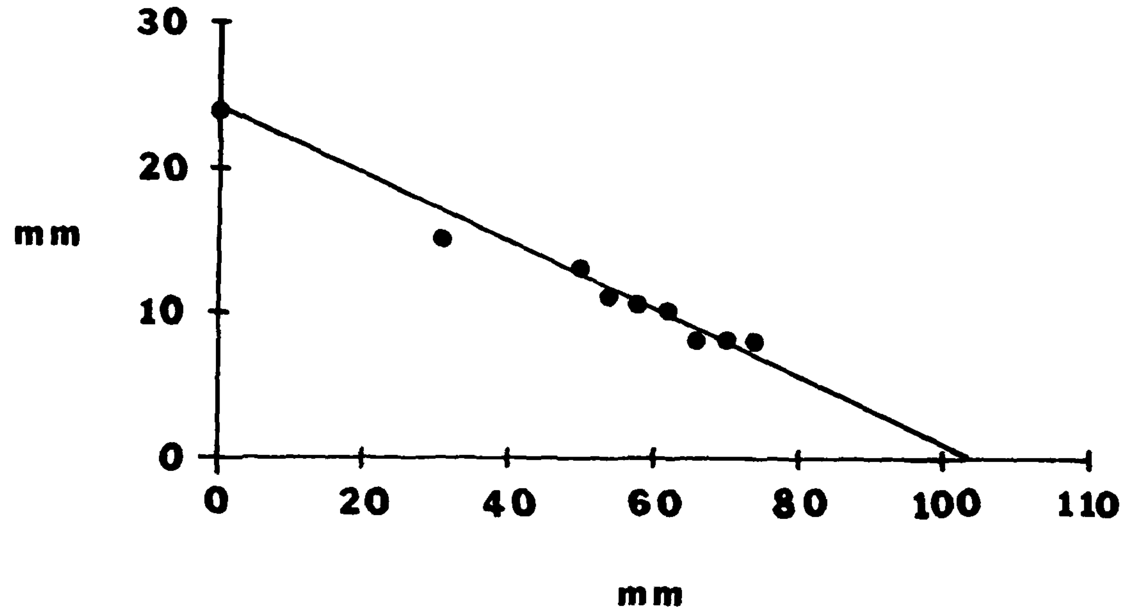


Figure III-1. Vertical Image Size vs. Distance from Lens.

III.4 Second Approach to Focal Point Determination

As apparent from the data in Appendix 4, the heat-sensitive paper did not serve as a suitable record of the focused beam beyond 74 mm from the lens. As a more exact determination of the focal point was desired, further trials were performed with more substantial materials.

Brass sheeting (0.005 in. thick) was placed in front of the focused beam, with little resultant effect. The brass was incrementally moved to, and through, the expected focal point. Even near the focal point there was no noticeable heating or discoloration of the brass. Repeated firings on the same piece of brass resulted in some discoloration, but the rate of change was too slow to be measured with available equipment. While the brass itself was not affected, the reflective properties of the sheeting caused a bright white flash and a sharp audible crack from the air between the lens and the sheet. It was presumed that these effects were the result of the ionization of the air or intense mechanical vibration, or both, caused by rapid heating of the air. The extent of this phenomenon varied, with the maximum visible and auditory effect occurring when the brass was located near the focal point (84-100 mm from lens).

Aluminum foil (0.001 in. thick) was chosen as the next material to be irradiated since it was considerably thinner than the brass. While the most noticeable phenomenon was still the flash and crack in the air, the aluminum foil was affected in ways unnoticed with the brass. The surface of the aluminum foil immediately behind the heated air was distorted away from the heated region. When several shots were fired at the same piece of foil, the distortion increased. The cause of the

distortion was assumed to be the shock wave produced by the rapid heating. This assumption has been supported by the fact that a small current of air can be felt by an observer holding his hand several millimeters from the heated region. While the aluminum was not detectably warm to the touch, even immediately after a shot was fired, it was observed that the distorted portion had been permanently stretched and hardened.

The above experimentation had convincingly shown that the LASER pulse was not sufficiently powerful to do direct, noticeable damage to reflective metal surfaces. In order to determine the specific focal point, then, a combination of materials was used; heat-sensitive paper was mounted on a piece of the brass sheeting. The paper would indicate the size of the beam, and the brass backing would prevent the paper from rupturing. This proved to be a successful method for examining the beam all the way to the focal point, and beyond. Appendix 6 displays the images produced on the paper at various distances from the lens. It is apparent from those images that the focal point is very close to 96 mm from the center of the lens and that the minimum size of the beam in the focal plane is approximately 2 mm high and 1 1/3 mm wide.

CHAPTER IV

IONIZATION DIAGNOSTICS

IV.1 Determining the Presence of Ionization

Chapter 3 indicated that the LASER pulse causes rapid heating of the air near the focal point. This phenomenon was found to be most dramatic when an obstacle was present in the path of the focused beam. At certain locations of the obstacle, a flash of visible light and an audible crack were observed coming from a region of air between the lens and the obstacle. (Photographs of the visible flash are found in Figures IV-18 and IV-19.)

In order to determine whether the observable flash was the result of atomic excitation alone, or the result of ionization as well, an experimental setup was devised by which ionization could be detected. Basically, the idea was to introduce a pair of electrodes in the portion of air intensely heated by the LASER beam. When the LASER is fired, the presence of ionized particles in the air would be confirmed by a flow of charge in the electrodes' circuitry.

IV.2 Development of the Experiment

Two sharply pointed steel probes were used as electrodes. In order to maintain a potential difference between them, the probes were connected to the terminals of a charged capacitor. The charge on the capacitor was initially established by a power supply, then the power supply was disconnected. In order to monitor any discharge of the capacitor, an electrometer was used to continuously display the voltage across the capacitor. The probes, with their tips slightly separated, were then placed in the region where the flash and crack had occurred,

and the LASER was fired. An immediate drop in the voltage reading on the electrometer indicated that ionization of the air in the region of the probes had indeed occurred.

The optics portion of this setup is shown in Figure IV-1. The large cabinet on the left contains the LASER cavity and alignment mirror. The dark tube in the center of the picture contains the focusing lens. Just to the right of the lens tube are the horizontally mounted probes, with electrical leads attached. Just right of the probes is a piece of flat copper sheeting, used as the obstacle mentioned above, to provide a flat reflective surface for the infrared radiation. The probe configuration is also shown in greater detail in Figure IV-2. The entire experimental setup is shown in Figure IV-3. The three units on the table in this photograph are, from right to left, the electrometer, the capacitor, and the power supply. A schematic of the electrical confirguration is shown in Figure IV-4. In this figure, the probes are indicated by the letter 'P', the capacitor by 'C', the electrometer by 'E', and the power supply by 'S'.

In order to determine whether or not the edge of the region of ionization could be consistently located, the probes, with the same tip separation, were then moved to a point along the optical axis which was beyond the region of the visible flash. After the capacitor was recharged, the LASER was fired. This time no discharge occurred through the probes, as indicated by an unchanged reading on the electrometer. The probe tips were then moved in small increments along the optical axis toward the region of ionization. At each position the LASER was fired and the electrometer reading checked. This process was continued

Figure IV-1. Optics Setup.

Figure IV-2. Probe Tip Configuration.

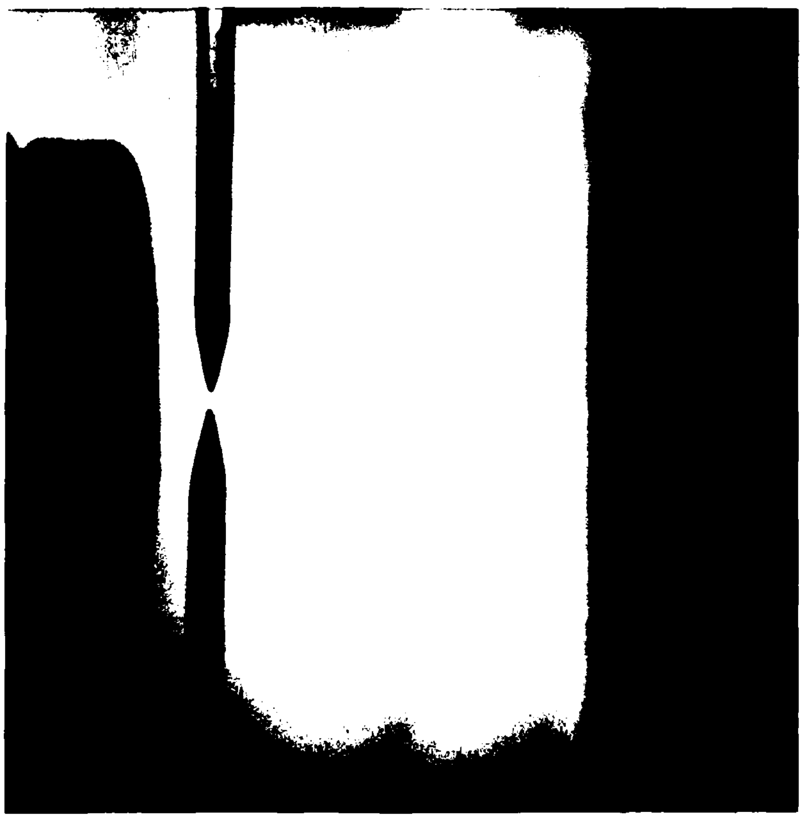


Figure IV-3. Experimental Setup.

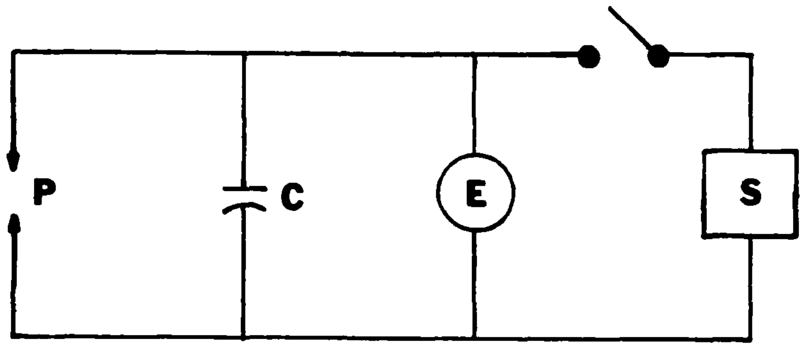


Figure IV-4. Electrical Configuration Schematic.

until the ionized region was entered, indicated by a discharge of the capacitor. Once the probe tips were within the ionized region, they were separated from one another by a distance wider than the region of the visible flash, and the LASER fired. As expected, no discharge occurred under this condition either. The probes were incrementally brought closer together until a discharge occurred. These procedures adequately showed that the region could be consistently located.

The next step was to establish a plan for methodically mapping the region where the ionization was sufficiently intense to permit a detectable discharge. Not knowing the actual bounds or structure of the region, an arbitrary starting point and arbitrary incremental changes were chosen. Where more or less detail was required as the experiment progressed, the bounds and/or increments were appropriately adjusted.

IV.3 Experimental Parameters

Parametric values which had to be chosen include the following: the initial probe tip separation and the incremental changes from that value, the range along the optical axis over which to move the probes and the incremental changes within that range, the distance between the

focusing lens and the reflecting surface, the voltage to which to charge the capacitor, and the number of LASER firings which would provide representative data.

The initial tip separation was chosen as 1 mm, as this distance was large enough to measure easily yet small enough to be well within the flash region over a significant portion of the optical axis. The increment of tip separation change was chosen as 1/2 mm, as this was both measurable and able to provide a sufficient number of data points within the flash region. This change increment was later increased to 1 mm where the gradient of data change became smaller. The range along the optical axis was chosen based on the space limitations between the lens and the reflective surface. Moving the probes within the range from 10 mm from the lens tube to 5 mm from the reflective surface (69 mm from the tube) provided sufficient coverage of the ionized region and avoided the problem of accidentally discharging through the tube or reflective surface. The incremental change within this range was chosen as 5 mm, as this appeared to provide the most reasonable number of data points. This value was reduced in the areas where the ionized region was entered or exited to more precisely locate the transition point.

The distance between the lens and the reflecting surface was chosen to provide the most dramatic, and consistent, visible and audible effects. This distance was also chosen because it placed the region of visible flash as far from the reflective surface as possible. As the flash tends to occur near this surface, moving the flash as far as possible from the surface allowed more measurements to be taken between the two. The lens to reflective surface separation which led to the most

suitable measurement conditions was 105 mm. 100 volts was chosen as the voltage placed across the capacitor, as this was the maximum full scale deflection provided by the electrometer. Full scale deflection was chosen to simplify reading the meter following partial discharges. Finally, when firing the LASER consistently resulted in total, or no, discharge of the capacitor, three shots were considered adequate. However, when there were different electrometer readings among the first three shots, a total of ten readings were taken to determine an average voltage-after-discharge value.

IV.4 Summarizing the Data

Data was collected for probe tip separations of 1, 1 1/2, 2, 2 1/2, 3, 3 1/2, 4, 5, 6, 7, and 8 mm. When the probe tips are placed in the path of the beam in front of the heat sensitive paper, their 'shadow' is recorded on the paper. The shadows of the probe tips at the above separations are shown in Figures IV-5 (a) through (k). The voltage data collected at each separation is presented in Figures IV-6 through IV-16, respectively. Voltage remaining on the capacitor after the LASER was fired is plotted vertically and the distance of the probe tips from the lens, along the optical axis, is plotted horizontally. Where values vary over some range, one standard deviation is shown by an error bar. Regardless of the probe tip separations in Figures IV-6 through IV-16, the focal point is always located at 96 mm from the lens and the reflective surface is located at 105 mm from the lens.

Moving from left to right on each figure, the horizontal location where the voltage drops from 100 V to some greatly reduced voltage is the place where the probe tips entered the region of ionization. The

(a) 1 mm

(b) 1 1/2 mm

(c) 2 mm

(d) 2 1/2 mm

(e) 3 mm

(f) 3 1/2 mm

(g) 4 mm

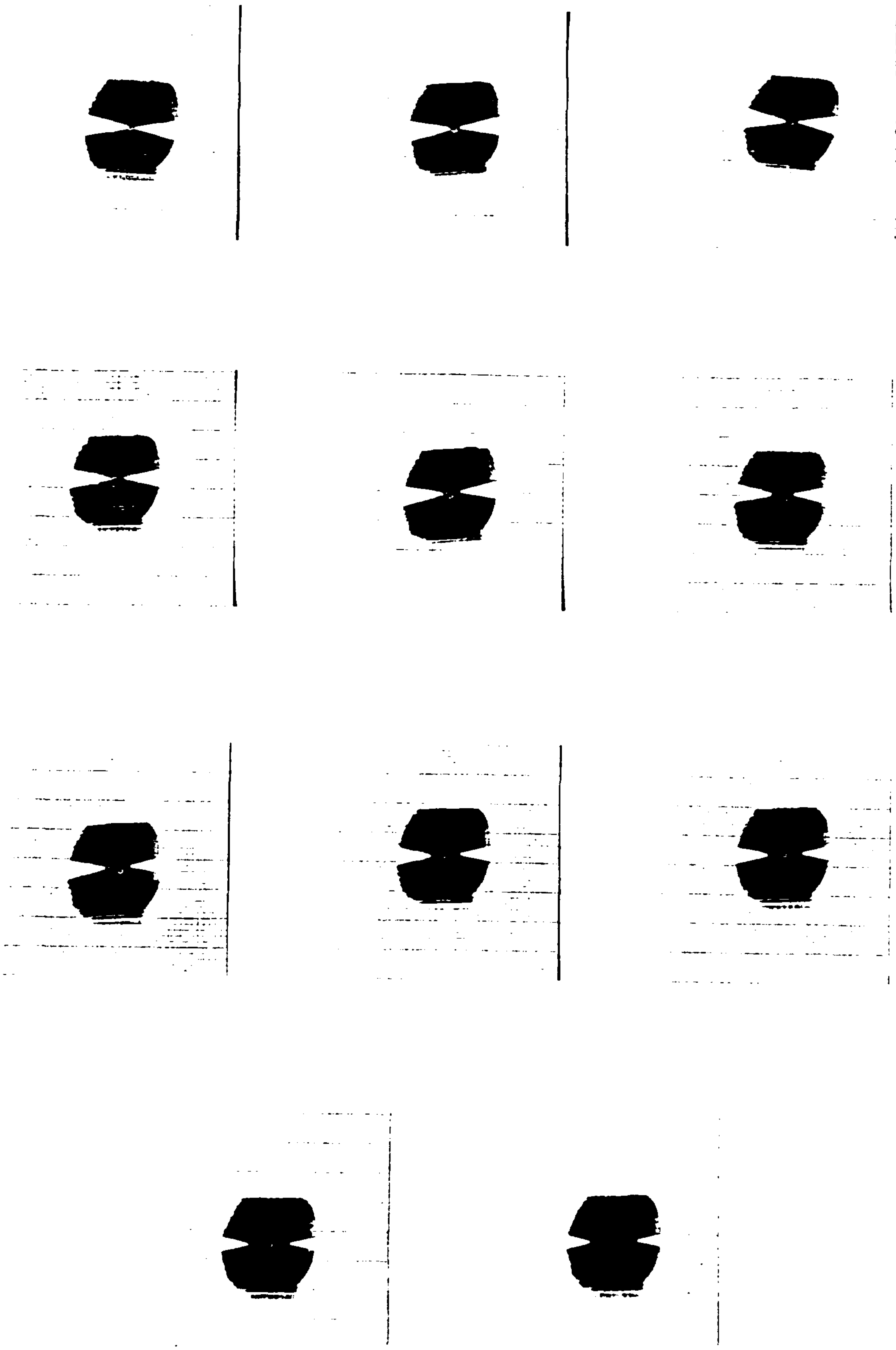
(h) 5 mm

(i) 6 mm

(j) 7 mm

(k) 8 mm

Figure IV-5. Probe Tip Separations.



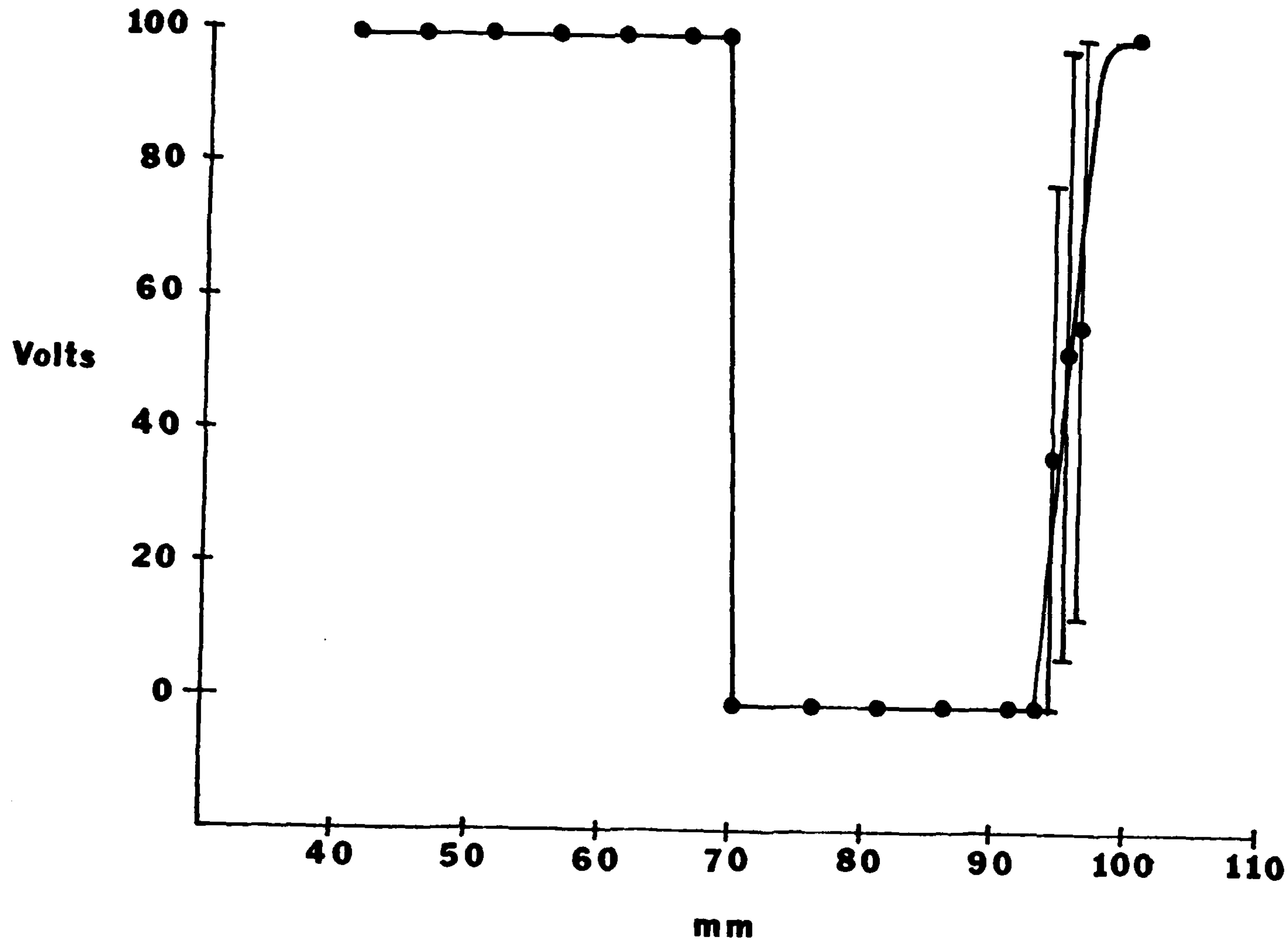


Figure IV-6. 1 mm Probe Tip Separation Data.

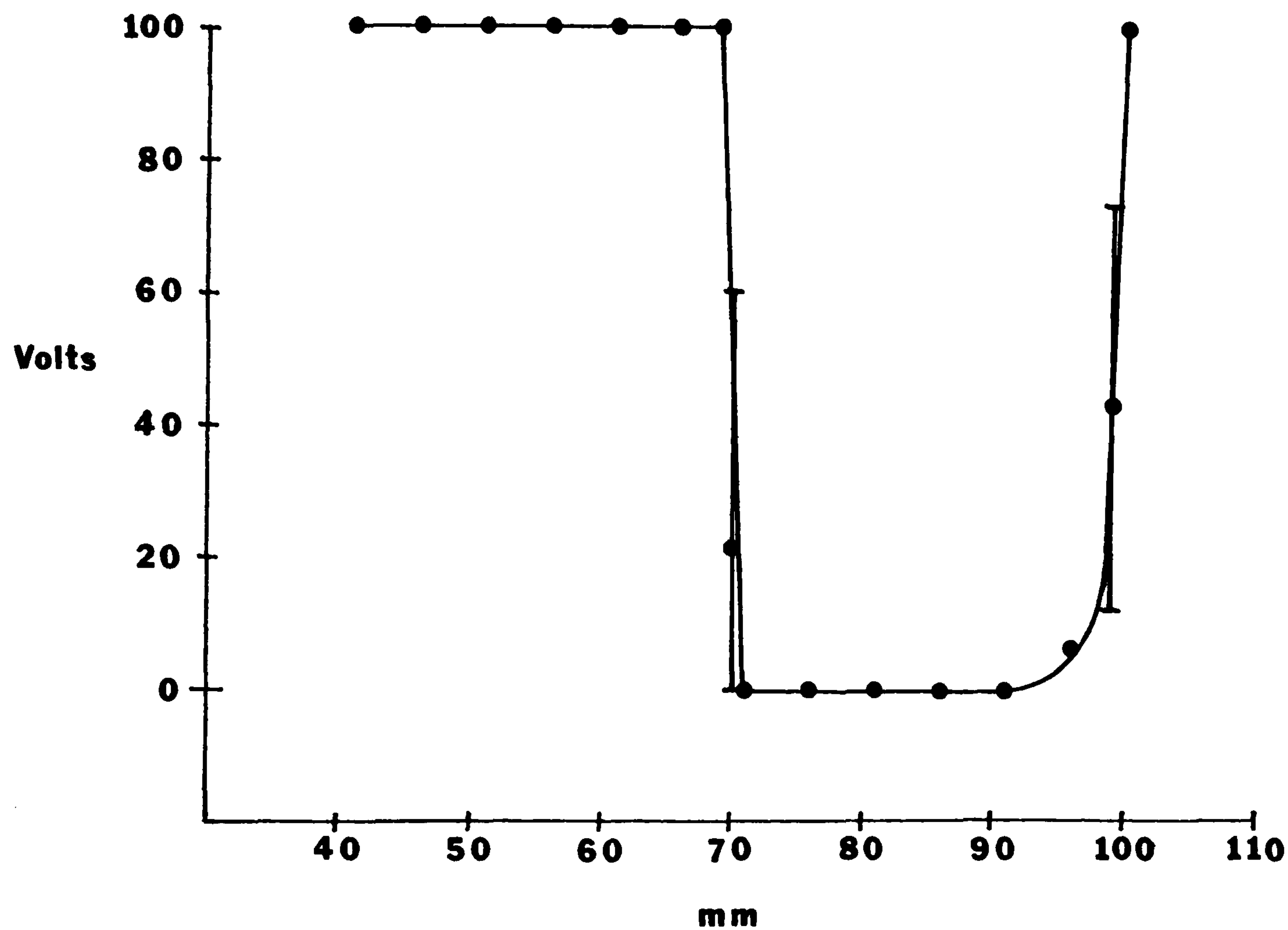


Figure IV-7. 1 1/2 mm Probe Tip Separation Data.

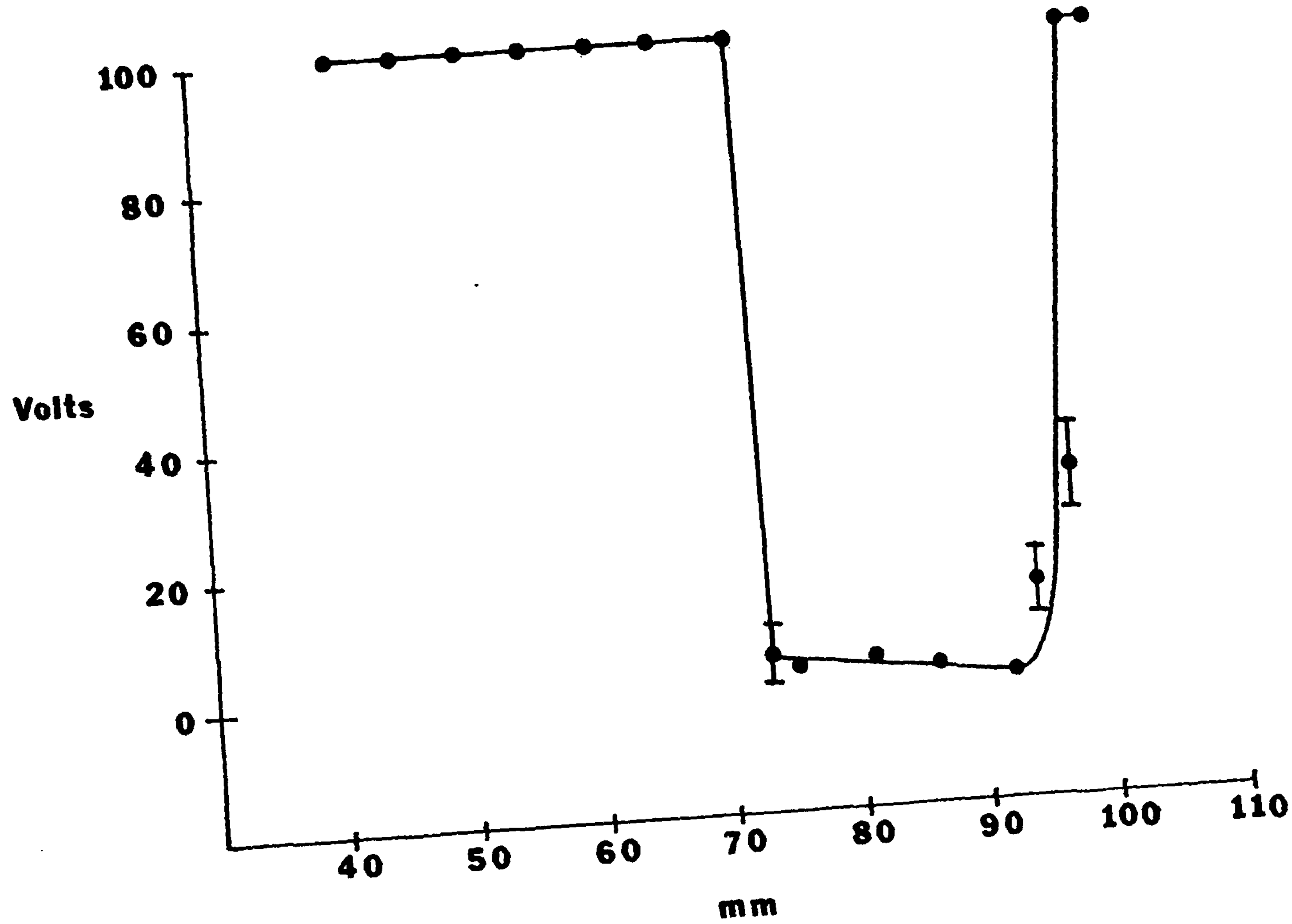


Figure IV-8. 2 mm Probe Tip Separation Data.

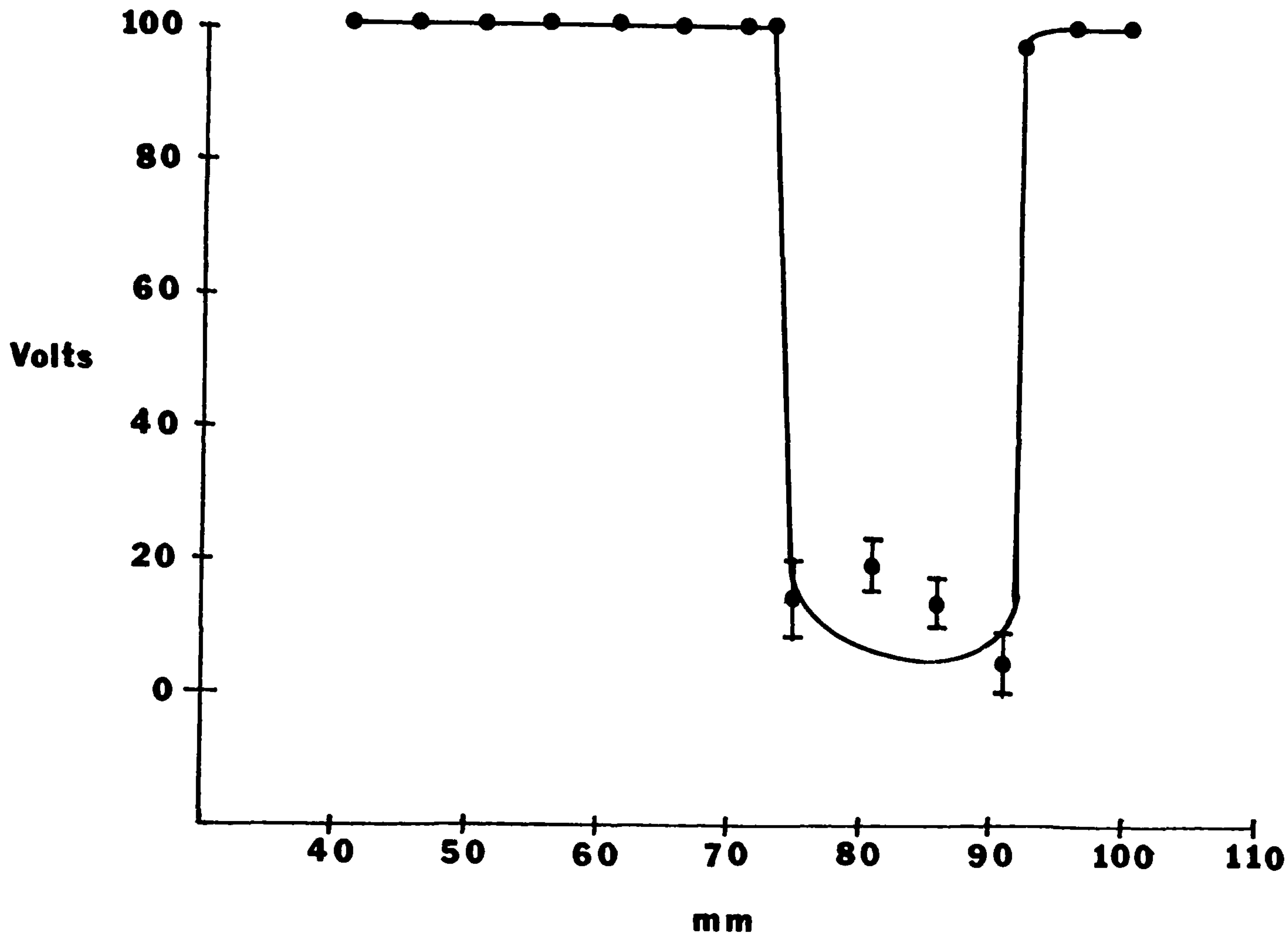


Figure IV-9. 2 1/2 mm Probe Tip Separation Data.

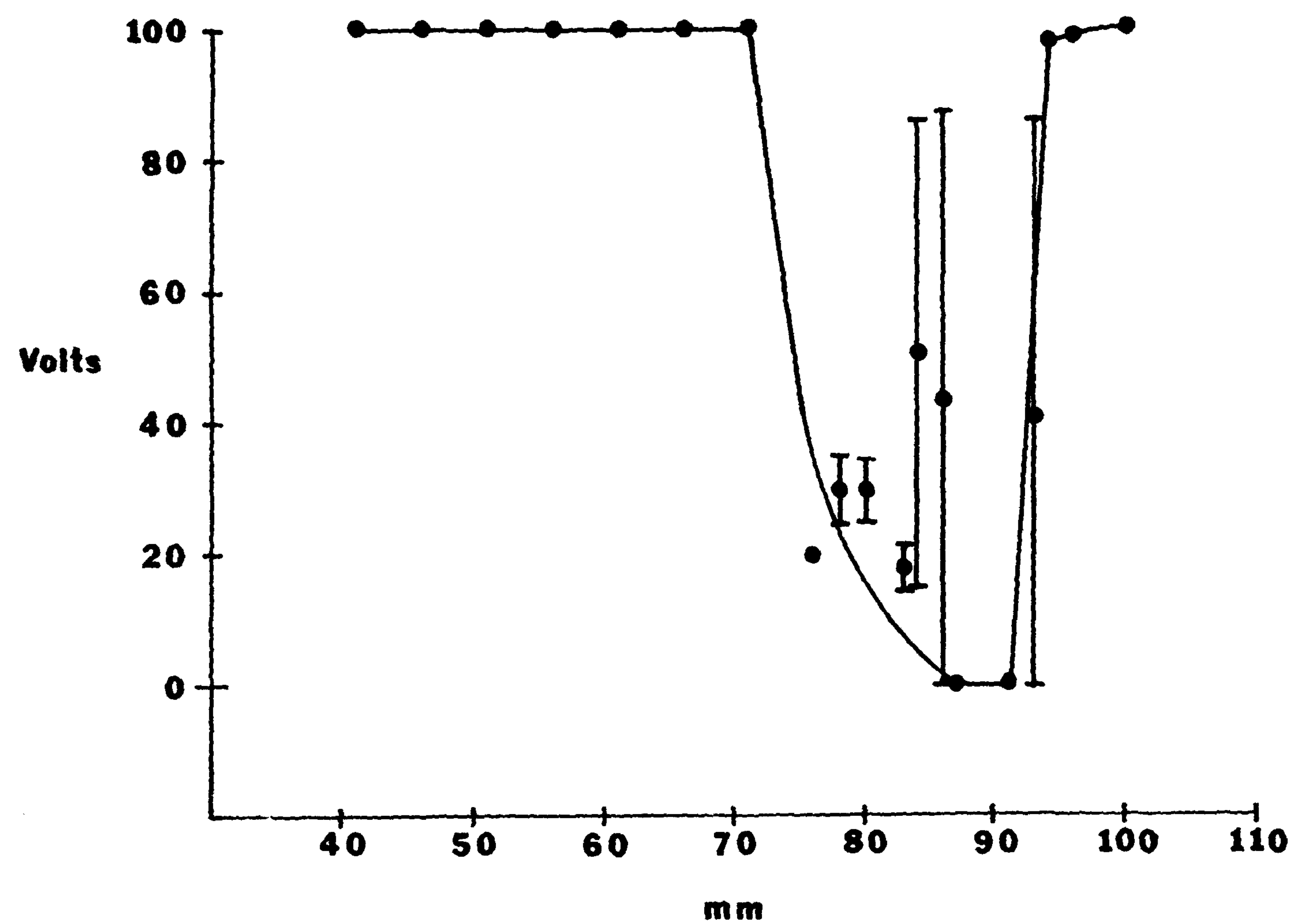


Figure IV-10. 3 mm Probe Tip Separation Data.

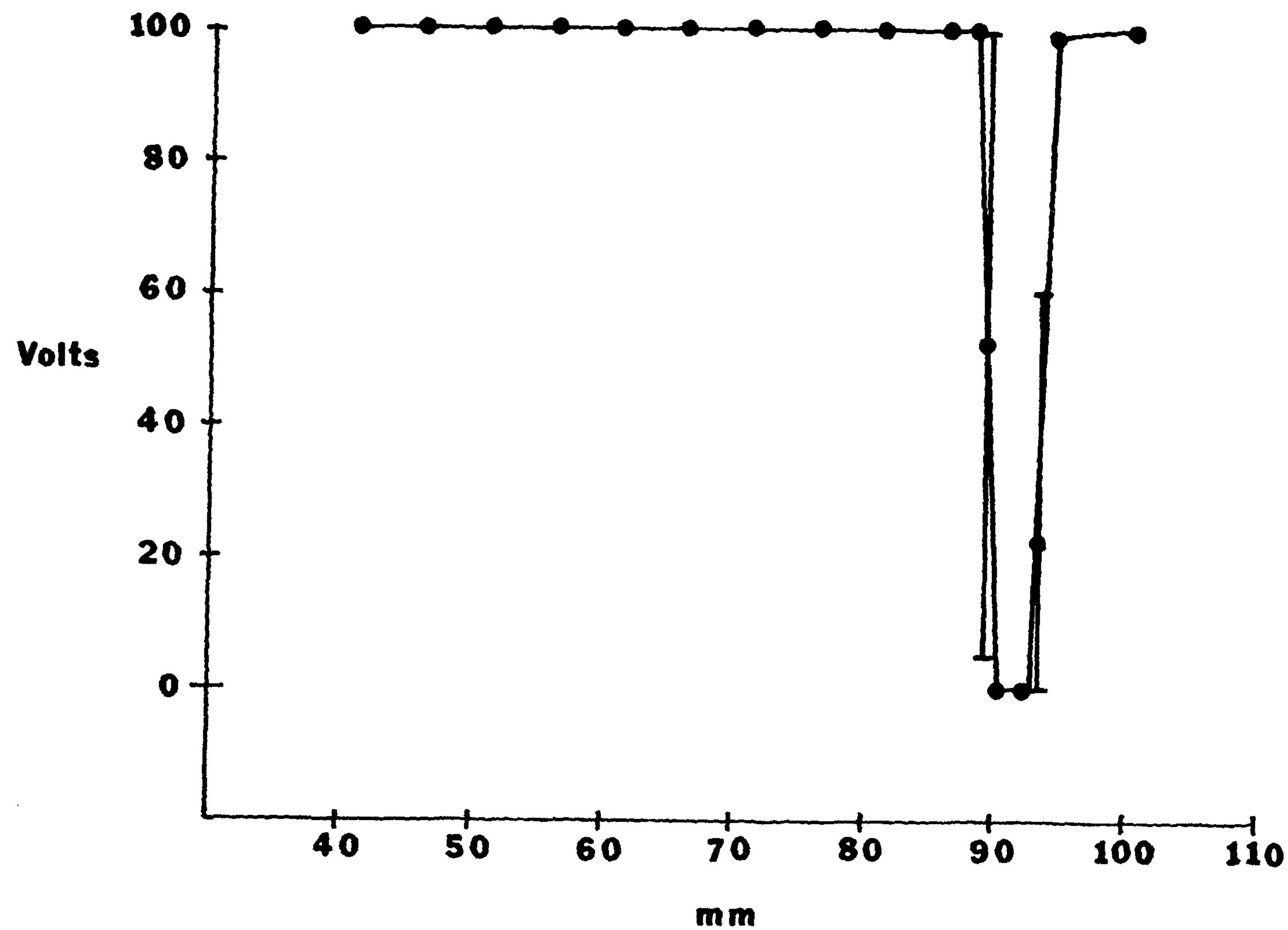


Figure IV-11. 3 1/2 mm Probe Tip Separation Data.

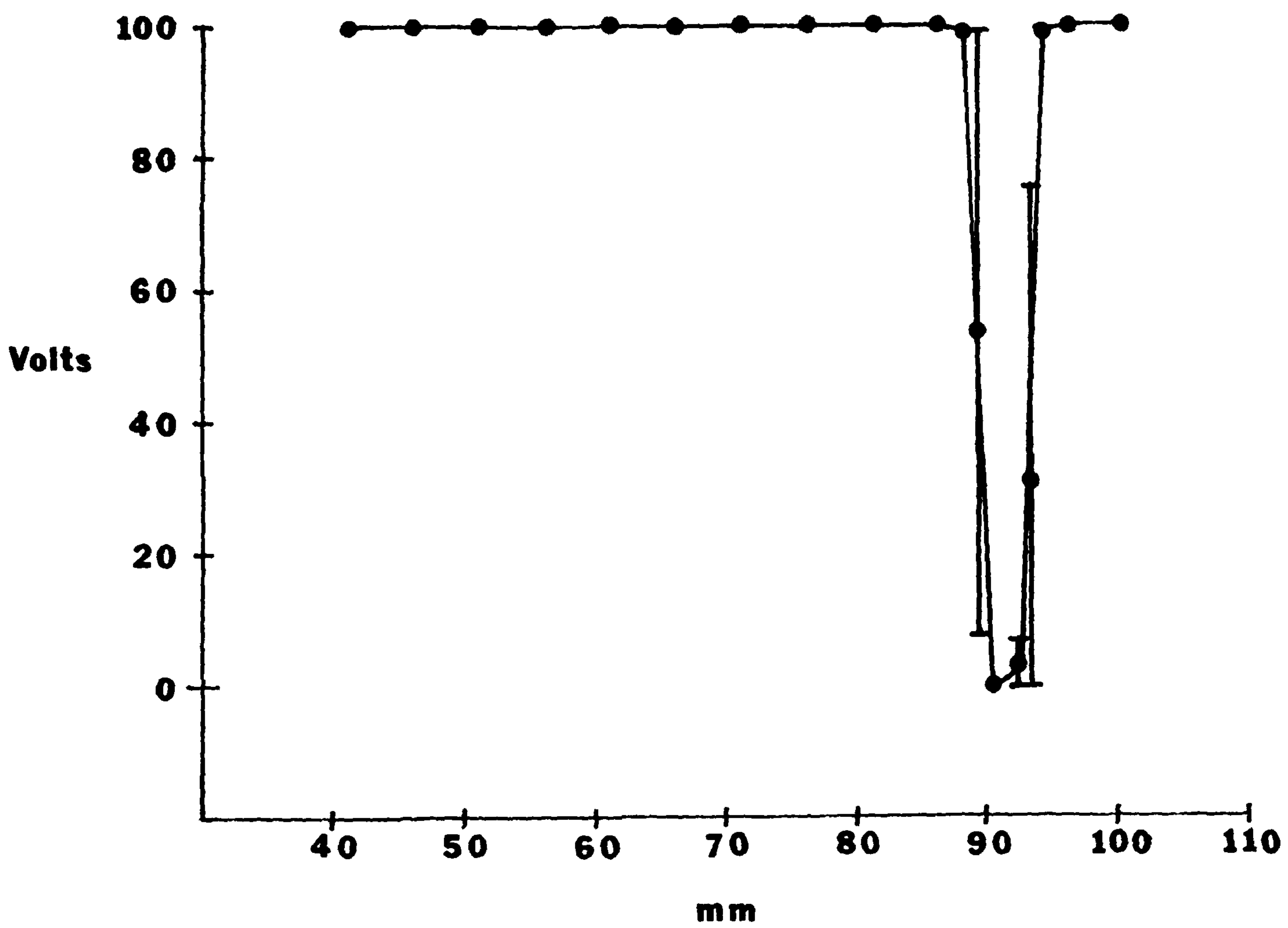


Figure IV-12. 4 mm Probe Tip Separation Data.

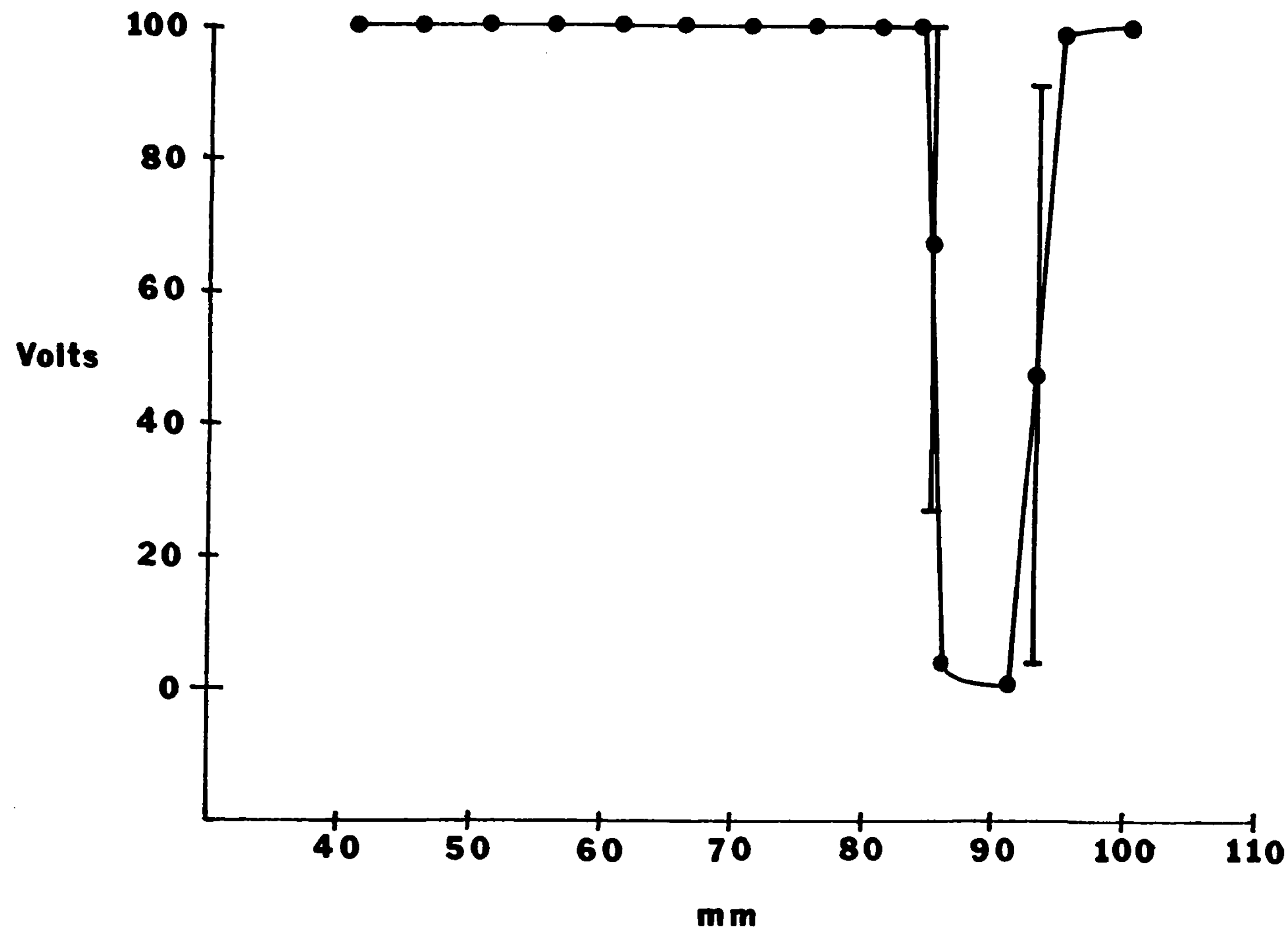


Figure IV-13. 5 mm Probe Tip Separation Data.

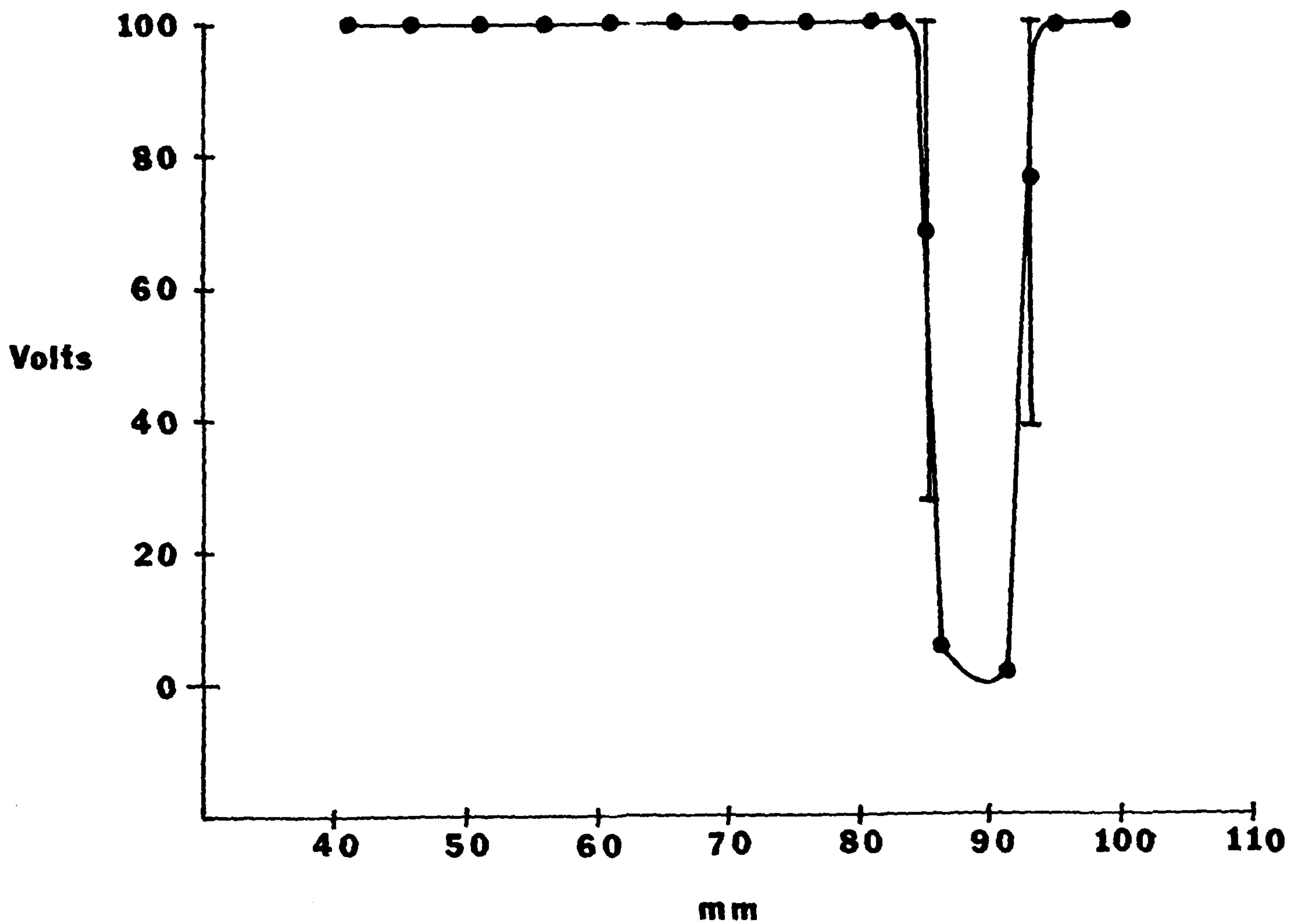


Figure IV-14. 6 mm Probe Tip Separation Data.

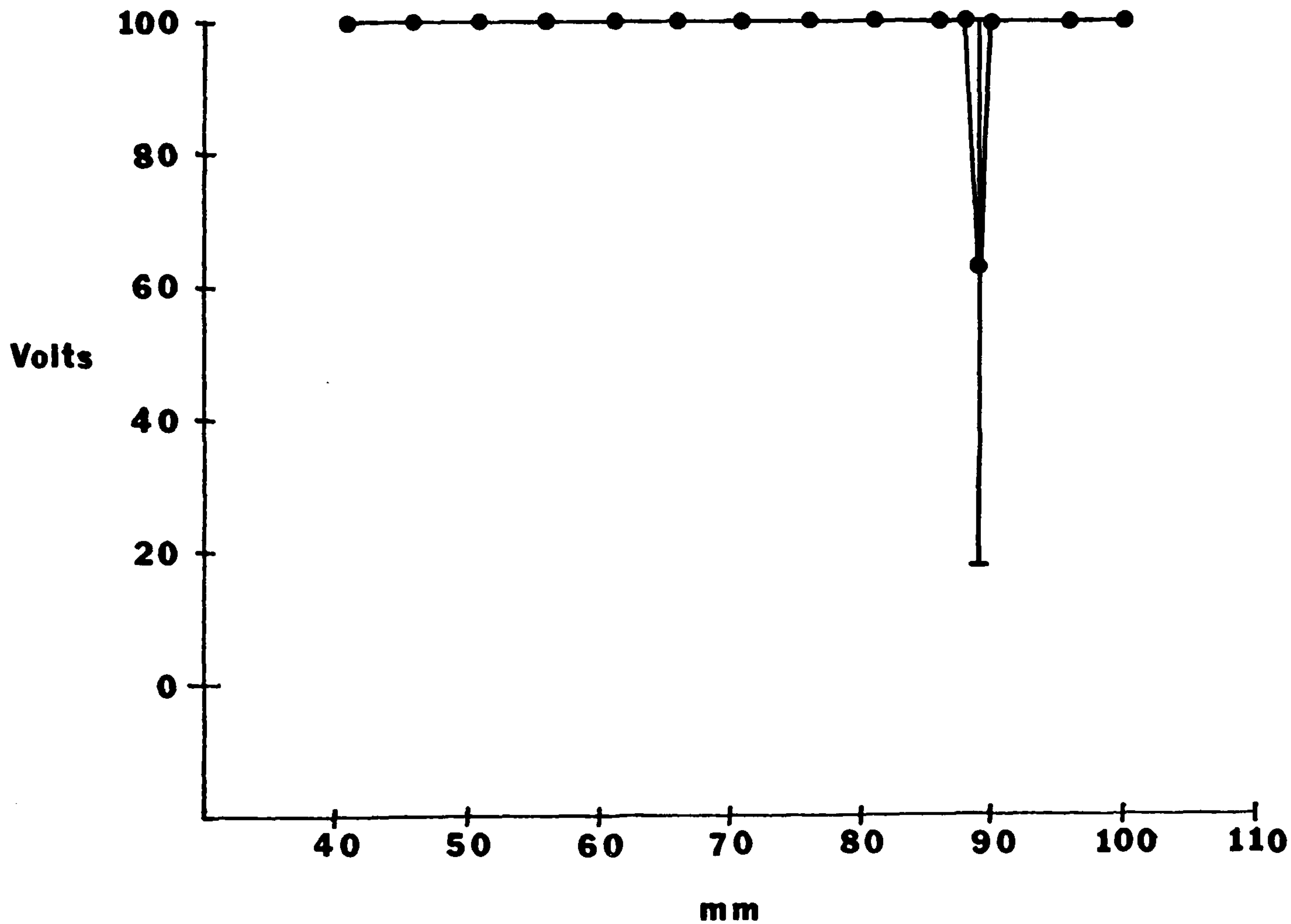


Figure IV-15. 7 mm Probe Tip Separation Data.

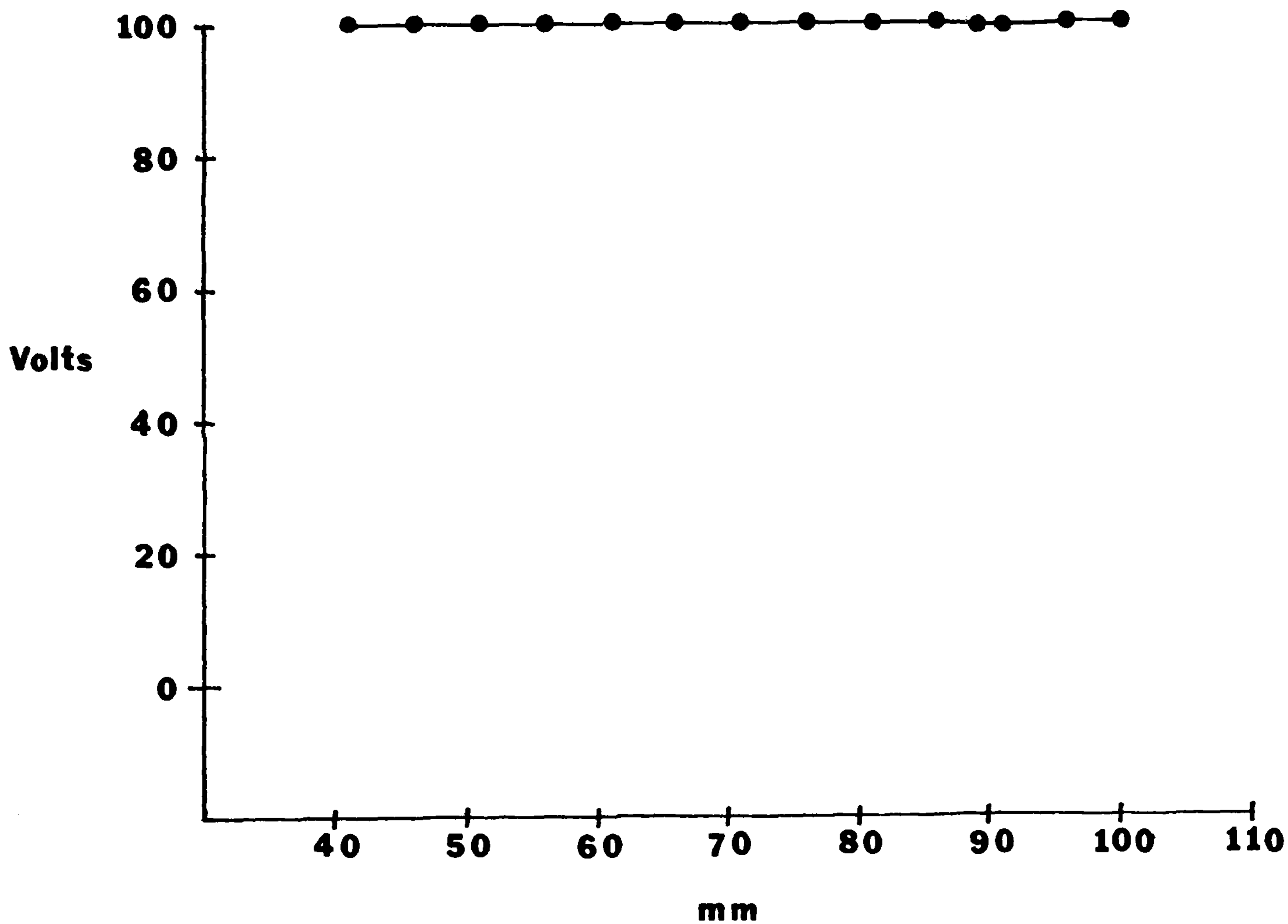


Figure IV-16. 8 mm Probe Tip Separation Data.

location where the voltage returns to 100 V indicates the point at which the probes exited the ionized region. In some cases, the transition appears to occur over a distance of several millimeters. This is probably due to the variability of the ionized region itself, discussed in more detail later. A wide spread in the voltage readings at one location was common within the transition regions. This was often due to the fact that the population was nearly evenly divided between large discharges and no, or small, discharges. This extreme variation indicates both the variability of the location of the ionized region from 'shot' to 'shot' and its sharp boundary for a given 'shot'. The limitations of this experiment did not allow control or precise measurement of this variation.

As the figures are studied together, it is clear that the ionized region extends for shorter distances along the optical axis as the probe tips are separated from one another by greater distances. It is also obvious that the ionized region is not a symmetrical ellipsoid, but is flattened on the end closer to the reflective surface. Both of these observations are consistent with the shape of the visible flash region.

The information provided by Figures IV-6 through IV-16 can be compiled to determine the overall shape of the ionized region. Plotting the separation of the probe tips vs. the locations at which the voltages after discharge are less than 50 V, the shape of the ionized region can be approximated. The result of plotting these values is shown in Figure IV-17. For clarity, the deduced outline of the region is shown above the plot of the data points.

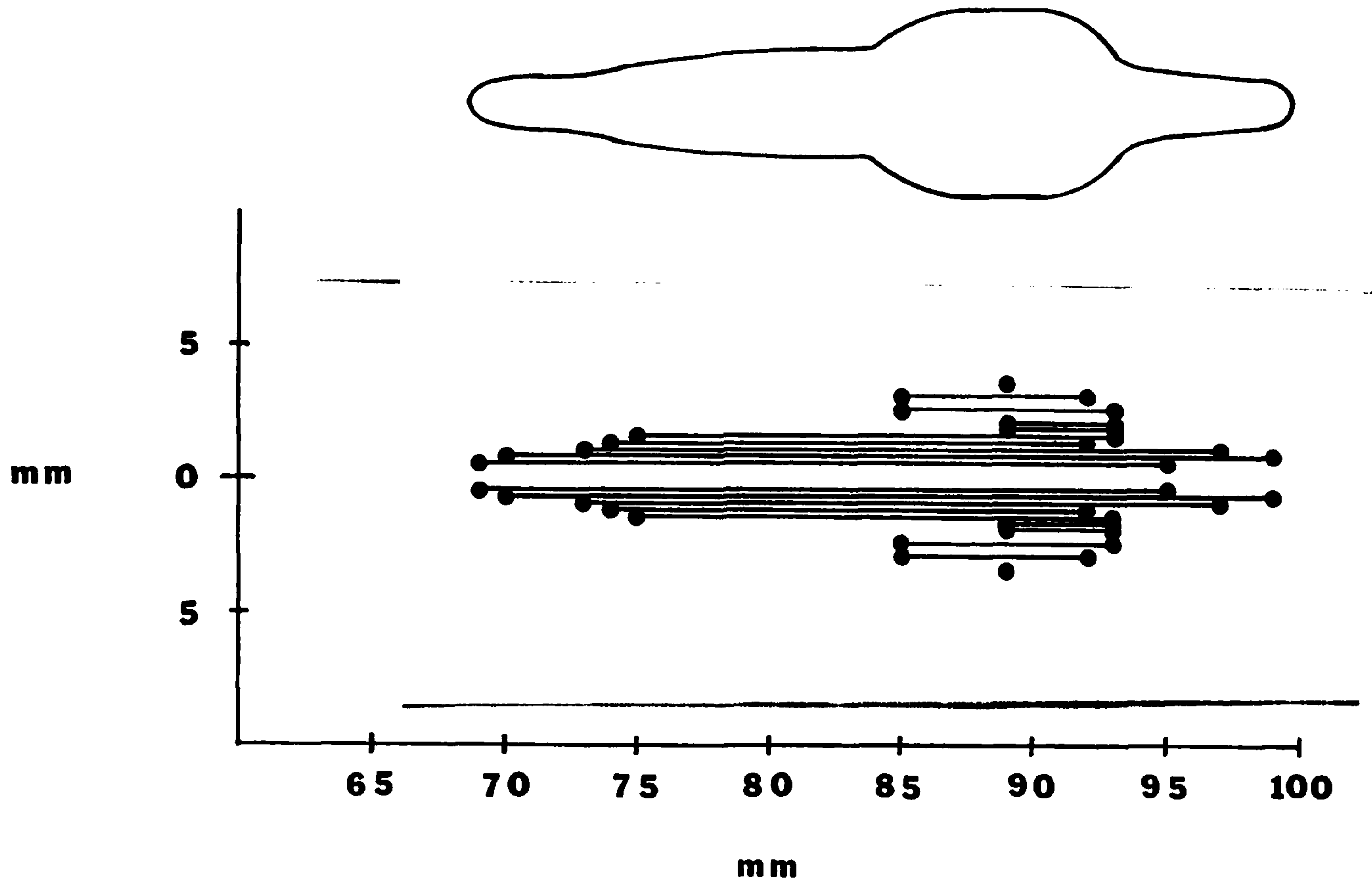


Figure IV-17. Approximation of Ionization Region.

IV.5 Limitations of the Experiment

As mentioned previously, the LASER's pulse duration may vary in a range from 0.1 to 20 microseconds. This wide variability will have a definite impact on the spatial distribution of the energy delivered by the LASER, and on the amount of power.

Response of the region of air heated by the LASER is also affected by the air itself. No attempt was made during this experiment to measure or control factors such as humidity, temperature, pressure, or composition of the air in the path of the beam.

Another factor which could not be accurately controlled was the time between pulses. Because the LASER's present configuration requires manual triggering, consistency of the time between pulses was totally dependent on the operator's ability. The effect of timing on this LASER's output has not been determined. Because the LASER's operation depends on fresh mix gas entering the cavity as the active medium, the time between firings is likely to be an important factor.

There were also uncertainties in the measurements that were made. Because the probes were affixed to the top of free-standing mounts, small vibrations of the mounts could cause a significant variation in probe tip separation. Even with reasonable efforts to stabilize the mounts and prevent vibrations, some undoubtedly remained.

Positioning of equipment from day to day and from trial to trial introduced variability into the results. Small changes in tip separation, reflective surface position, and lens position could have a noticeable affect on the results. Even when attempted, the configuration which resulted in one set of data could not be exactly duplicated. This

fact alone demands that the data presented here be used more qualitatively than quantitatively.

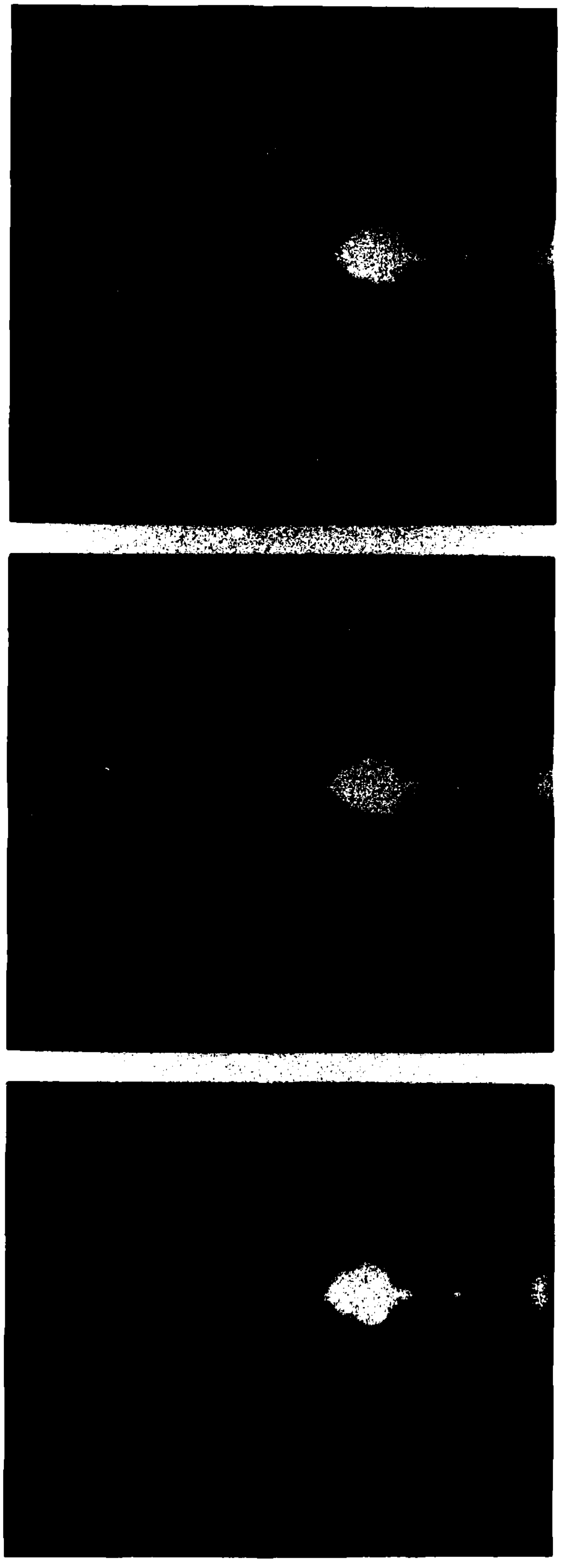
The reflective surface and the probe tips were gradually discolored by heating and oxidation. (The discoloration of the reflective surface is apparent in some of the photographs as a band of rings around the center of the beam.) There was no attempt to measure or correlate this gradual change with other observations, given that the variation of results from one firing to the next was so great.

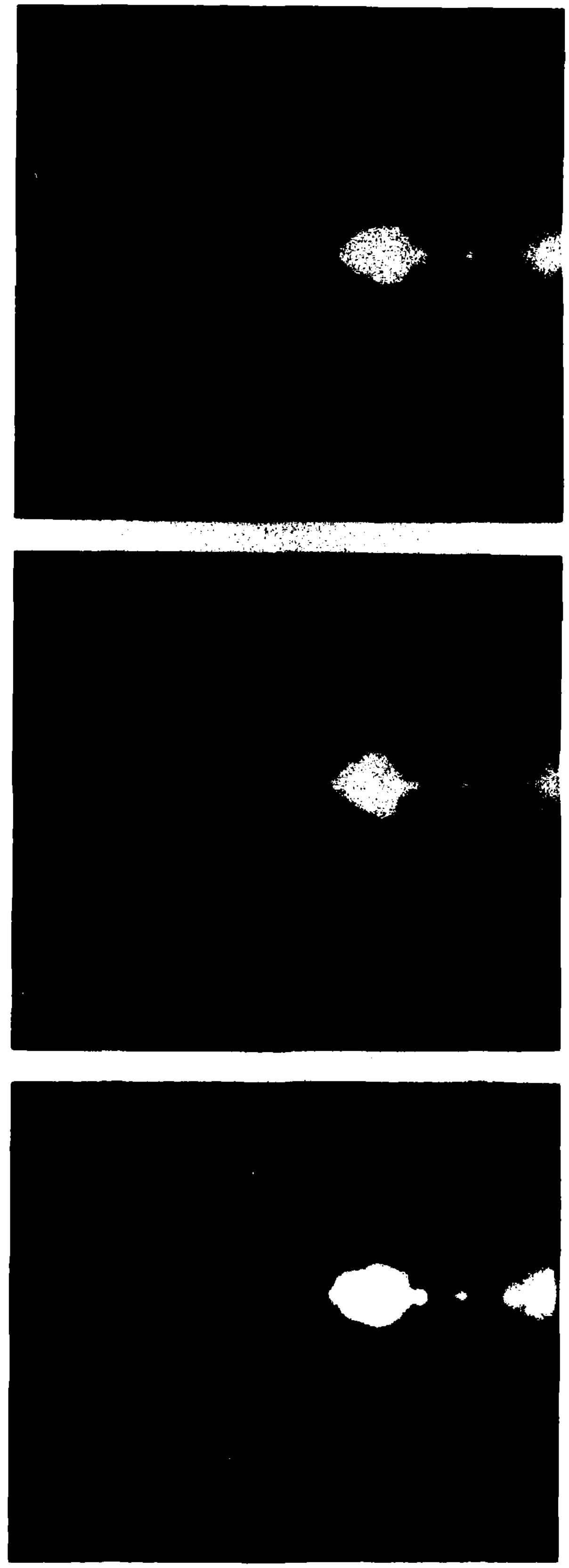
Some appreciation of the variability of the response of the air can be gained from the photographs in Figures IV-18 and IV-19. The six photographs in Figure IV-18 were all taken with the LASER and experimental setup unchanged between firings and within several minutes of one another. The probes were not part of the setup for these photographs. The photographs in Figure IV-19 were taken when the probes were present and completely discharging the capacitor. In Figure IV-19 (a), the probe tips were separated by 3 mm and were located 91 mm from the lens (5 mm closer to the lens than the focal point). In Figure IV-19 (b), the tips are 5 mm apart and still located 91 mm from the lens. In Figure IV-19 (c), the tips are 3 mm apart and located 86 mm from the lens. The significant observation from this figure is that any effect on the shape of the ionization region caused by the probes is small compared to the normal variation of the region, as seen in Figure IV-18.

IV.6 Conclusions

The experiment described above shows that a region of air contains charged particles when it is irradiated by a focused pulse from the LASER. The region is collocated with a flash of visible light and occurs

Figure IV-18. Visible Flash from Ionization Region.



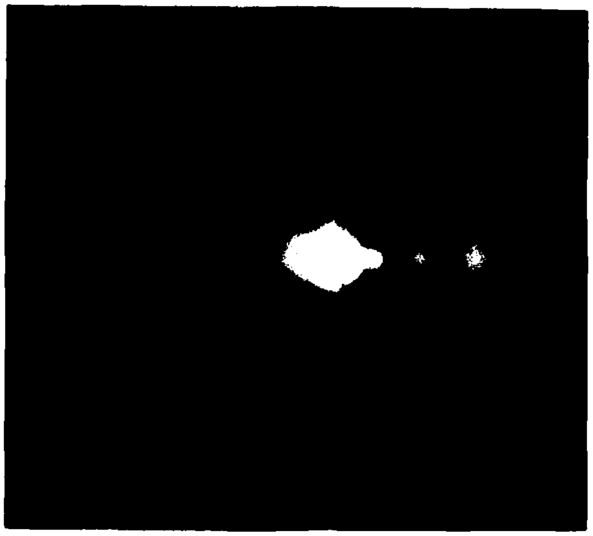


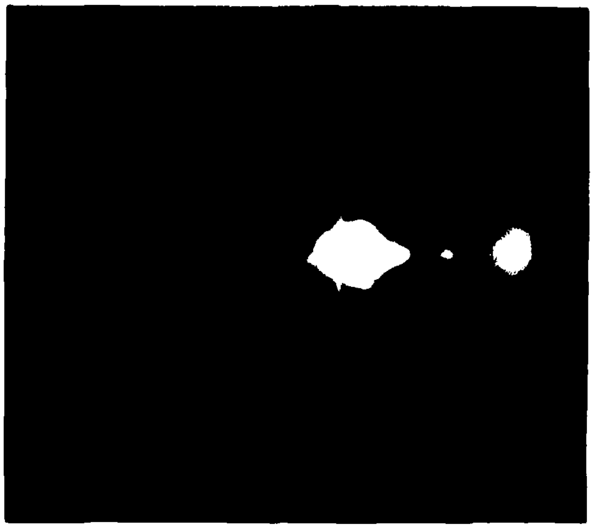
(a)

(b)

(c)

Figure IV-19. Visible Flash and Probes during Discharge.





simultaneously with the flash and a loud audible crack. These effects only occur consistently when an obstacle is properly located in the path of the LASER pulse.

The picture that emerges is as follows. Some of the focused infrared energy of the beam is converted into vibrational energy of the air molecules. This causes rapid heating and expansion of the air in the affected region. The rapid expansion produces a shock wave, heard as a loud audible crack. The violent action of the molecules also results in some of the atoms' electrons being knocked from their orbits, producing a plasma of ions and excited atoms. As the electrons are subsequently pulled back into stable orbits, visible radiation is given off in the form of the bright white flash.

Knowing the initial and final voltage drops across the capacitor and the amount of capacitance of the capacitor, the change in charge can be computed. A voltage drop of 100 volts, times the capacitance of 10^{-5} farads, gives a total charge of 10^{-3} coulomb. This amount of charge indicates that the equivalent of 6.25×10^{15} singly-ionized atoms are involved in the discharge process. The number of atoms in a cubic mm of air at STP is approximately 2.67×10^{16}. Thus, the equivalent of all the atoms in 0.234 cubic mm of air at STP are involved. (From the ionized region outline shown in Figure IV-17, the volume of ionization, as detected by the probes, is approximately 432 cubic mm.) This indicates that an average of 0.054 % of all the air atoms in the ionized region take part in a total discharge of the capacitor. Lesser discharges of the capacitor indicate a proportionally smaller number of atoms involved. It should be emphasized that this is only a very crude estimate. Some atoms

may be more than singly-ionized and some none at all, the air is certainly not at STP, and it is unlikely to be pure (as discussed below).

The rapid expansion of the air as it is heated is macroscopically detectable. The force of this pressure wave was sufficient to form a bulge in the aluminum foil from just one pulse, as described in Section III.4. The pressure is also easily felt by holding one's hand within several mm of the beam path as the LASER is fired. The rapid pressure change constitutes a shock wave which is loud enough to require ear protection for continuous operation.

It is tempting to assume that the bright flash and shock wave are triggered by the addition of reflected energy to the energy directly focused by the lens. The maximum response is observed when the reflective surface is beyond the focal plane. This is also the configuration for which the addition of the reflected energy to that already concentrated near the focal point provides the highest energy density. The largest portion of the visible region of response by the air is located just in front of the focal plane. Apparently, the energy density in this region is least attenuated by the air and/or the initial effects of heating. The small 'tail' is located at, and just beyond, the focal plane. Apparently, there is still enough focused energy in this region that, even with some attenuation of the energy density, the flash is produced.

If the reflection of a part of the beam back on itself, near the focal plane of the lens, is required for the LASER pulse to produce the observed effects, the quality of that reflection seems to be

comparatively insignificant. For instance, the metal sheeting used throughout this experiment may be rotated about a vertical axis perpendicular to the beam path and the observed response in the air is still obtained. The surface was even found to trigger the bright flash and loud crack when turned parallel to the beam path. Interestingly enough, in this configuration, the flash occurs on both sides of the sheet at the same time. Neither is a flat surface required. A thin cylinder (a 0.035 in. diameter metal wire) also triggers effects very similar to those produced with the flat surface. Additionally, the material used seems relatively insignificant. In addition to metal surfaces, all of the following were tried: paper, wood, cardboard, plastic, cloth, and leather. Even when some damage was done to these materials, the characteristic flash and audible crack were always present. (Without an object near the focal point of the LASER beam, these effects did not occur.) While in some cases variations of the shape and color of the flash were apparent, the basic features of the shape observed in the photographs of Figure IV-18, a main body with a smaller 'tail' toward the obstacle, were clearly present. These results suggest that the observed effects may be due, in part, to the ejection of material from the surface of the obstacle.

CHAPTER V

RECOMMENDED FUTURE WORK

V.1 Analyzing the Region of Ionization

A number of methods for doing further analysis on the region of ionization became apparent as the above experiment was being performed. The probes used in the above setup were rather large and difficult to control. Smaller probes which can be more easily maneuvered will allow more precise and consistent analysis of the ionization cloud. The probes should be configured in a number of different relationships to determine the various characteristics of the cloud.

Analysis of the effect of the electric field established by the probes may be better understood by using voltages other than 100 V. If the electric field does affect the shape of the region, a much smaller voltage may provide a more accurate determination of the shape. A smaller voltage and a larger capacitance may prove to be a more sensitive combination.

Spectral analysis of the visible light produced by the ionization may provide information on the types and relative quantities of the molecules involved. Accurate pointing of the spectroscope may allow resolution of different parts of the ionization cloud. As mentioned above, different obstacles sometimes resulted in visible color differences, suggesting the presence of vaporized atoms. The spectrum of the cloud may give further insight into its composition and cause.

The angle, the shape, and the composition of the obstacles placed in the beam path can all be varied. In addition to flat surfaces used above, cylinders, balls, and curved mirrors may be tried. The distance

from the lens to the obstacle should be varied, with the structure of the cloud examined at each point. For example, the variation of cloud shape using different distances is obvious from the series of photographs in Figures V-1 (a) through (j). In these photographs, the distance between the lens and the reflective copper surface was changed for each firing; all other conditions remained the same. The photographs were taken when the distances between the lens and reflective surface were 70, 75, 80, 85, 90, 95, 100, 110, 115, and 120 mm, respectively. (The small vertical lines at the top and bottom of each figure indicate the location of the reflective surface for all photographs in that figure.) These photographs should be compared to the series in Figure IV-18, in which the distance between the lens and the reflector was held at 105 mm.

V.2 Analyzing the Shock Wave Produced by Ionization

Analysis of the shock wave produced by the rapid heating of air may prove as interesting and challenging as analysis of the ionization produced. Various surfaces positioned around the region of ionization may be used to alter the intensity and duration of the shock wave.

V.3 Beam Diagnostics

Except for basic alignment of the mirror, no analysis of the LASER beam itself has been accomplished. Diagnostics should begin with a spectral analysis of the beam, a power spectrum analysis, and a determination of the beam's divergence.

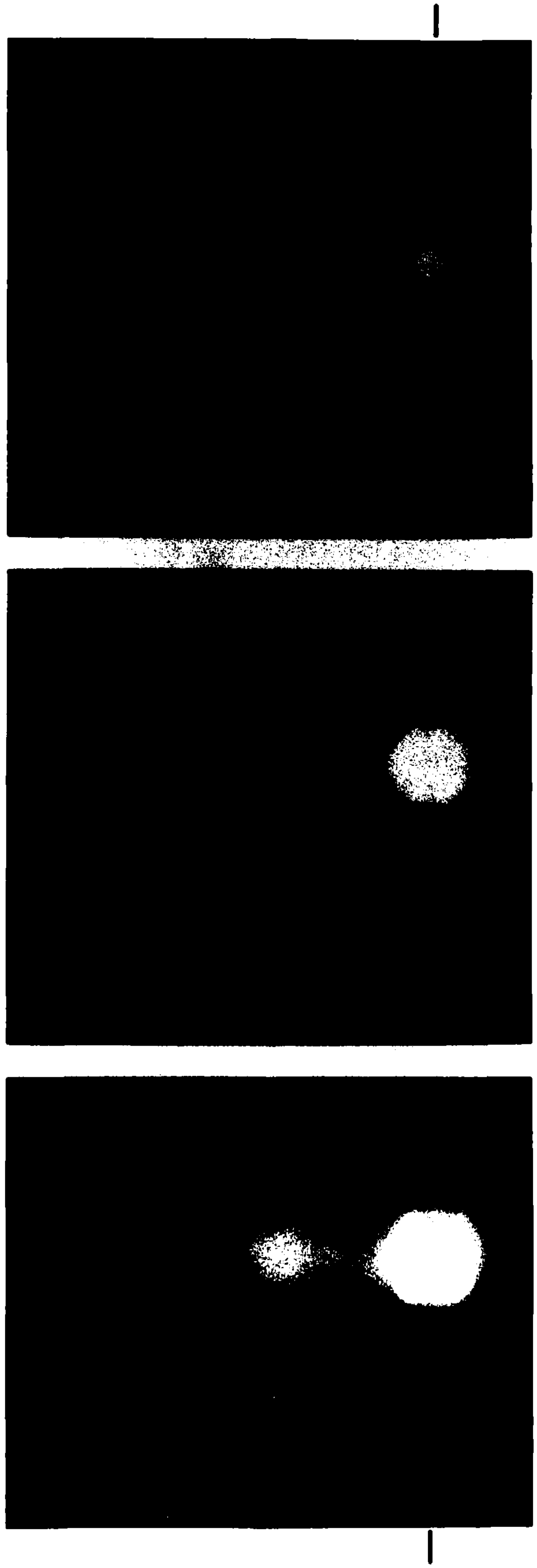
Another area which may prove interesting is that of beam absorption, by the atmosphere and other gases. This would offer an expansion of the work in spectral analysis, mentioned above. With LASERs

(a) 70 mm

(b) 75 mm

(c) 80 mm

Figure V-1. Ionization Flash with Reflective Surface Changes.

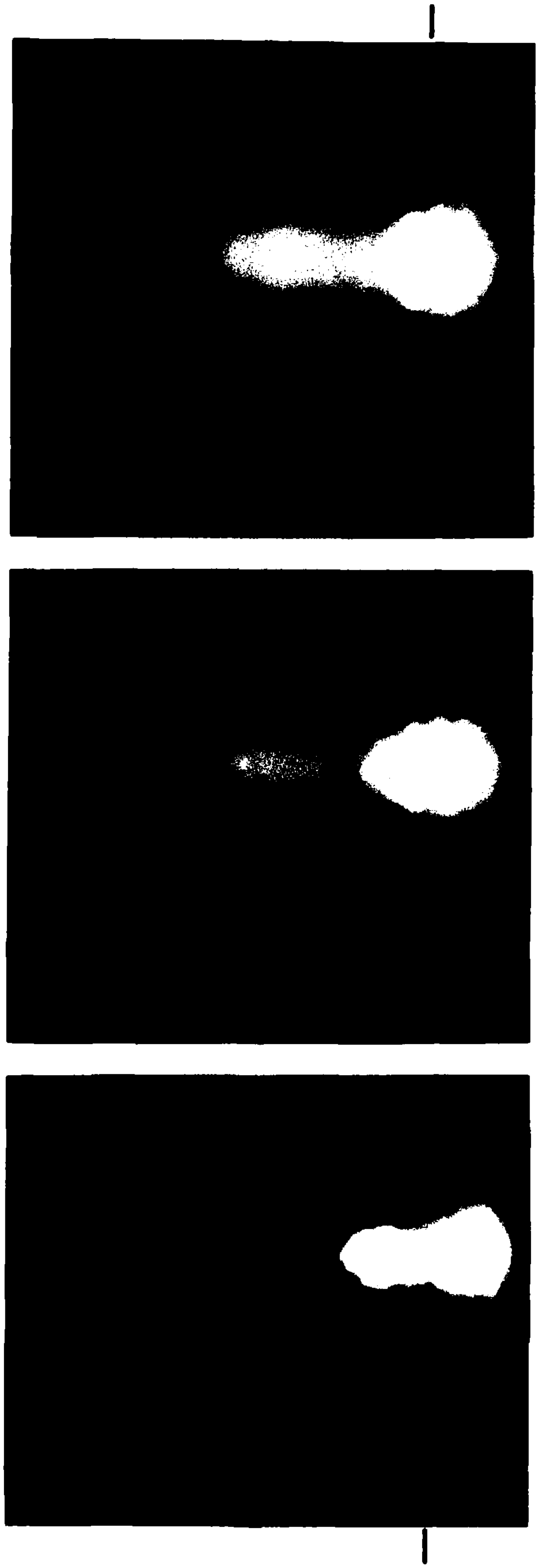


(d) 85 mm

(e) 90 mm

(f) 95 mm

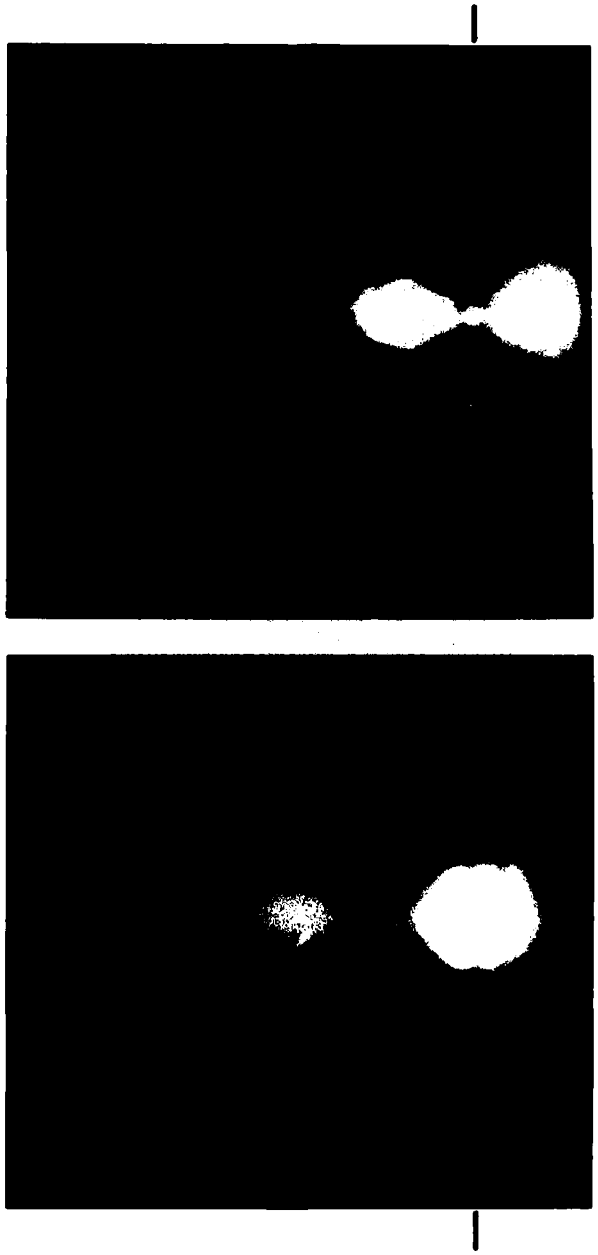
Figure V-1. Ionization Flash with Reflective Surface Changes.



(g) 100 mm

(h) 110 mm

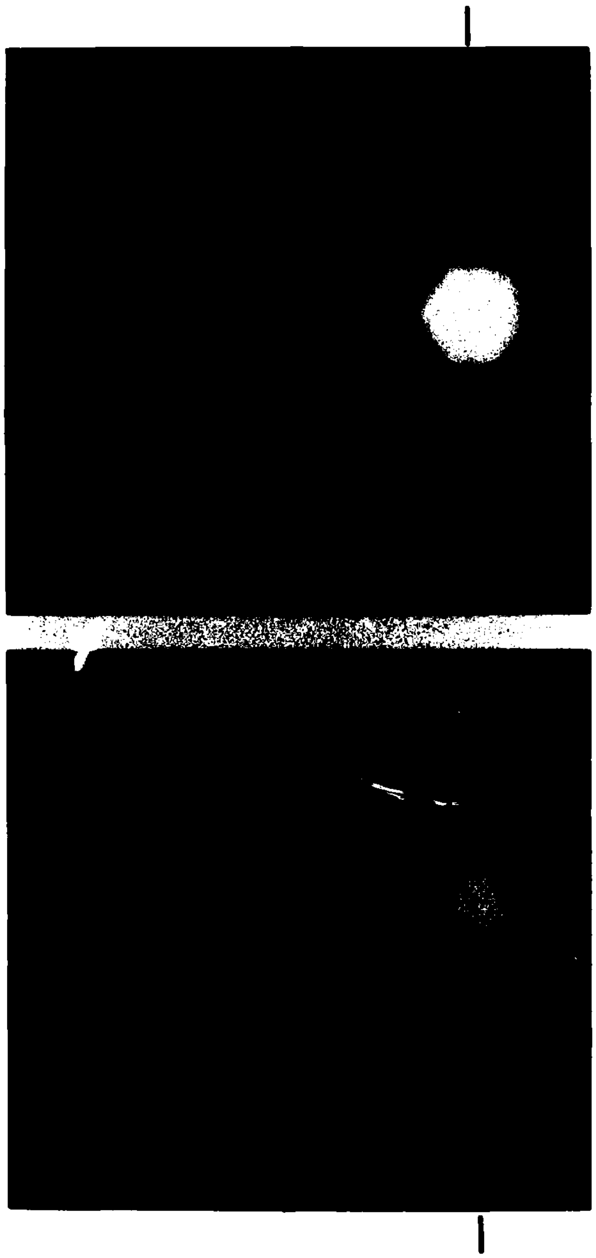
Figure V-1. Ionization Flash with Reflective Surface Changes.



(i) 115 mm

(j) 120 mm

Figure V-1. Ionization Flash with Reflective Surface Changes.



rapidly becoming a primary means by which to transfer energy long distances through the atmosphere, work in this area may prove very worthwhile.

V.4 Pulse Diagnostics

Work in this area should center around determining the temporal and total power characteristics of the pulse. The wide range of advertized pulse durations for this LASER could make this an extremely challenging task. Effects of the time between shots and the exact gas mix ratios used in the cavity should be examined as part of this study. Because variability of the pulse duration and power affects most of the other LASER characteristics mentioned above, the results of this work may provide a foundation for all other work done with the LASER.

V.5 LASER Diagnostics

This area includes a number of topics involving the LASER as a whole. Variation of the gas flow rates and pressures may be done to determine the optimum operating configuration. Additional work with intra-pulse timing may determine heating rates of the cavity or electrical components within the LASER. For those specifically interested in LASER design, a study of component wear or accessibility may indicate where general improvements can be made.

APPENDIX 1

SAFETY

The following warnings are extracted from the system Operator's Instruction Manual and repeated here for emphasis:

DO NOT PLACE EXPOSED SKIN IN THE PATH OF THE BEAM AND DO NOT LOOK DIRECTLY INTO THE BEAM PATH.

COMPONENTS SHOULD BE REPLACED ONLY WITH UNITS THAT ARE SPECIFIED OR EXACT MANUFACTURER'S EQUIVALENTS.

FUSES MUST ONLY BE REPLACED WITH THE SIZE AND TYPE INDICATED BESIDE EACH FUSEHOLDER.

THE USE OF CONTROLS OR ADJUSTMENTS OR PERFORMANCE OF PROCEDURES OTHER THAN THOSE SPECIFIED HEREIN MAY RESULT IN HAZARDOUS RADIATION EXPOSURE.

Warning labels are also affixed at appropriate external locations of hazardous areas of the LASER system. Their instructions should be obeyed during all phases of operation.

In addition to the items already mentioned, the following procedures are strongly recommended during operation of the LASER:

1) All persons in the immediate vicinity of the LASER should wear eye protection when the LASER is being fired. Adequate protection consists of standard eye glasses or lab goggles, as both glass and plastic have been shown to be opaque to the emitted infrared radiation.

2) During repeated firings of the LASER in which the focused beam is being used to rapidly heat ambient air, ear protection should be worn by all persons in the immediate

vicinity of the LASER. Adequate protection consists of earplugs or headset, as both filter out the hazardous high frequency portion of the loud audible crack produced by the heating.

3) The Auto/Manual On Keyswitch on the Remote Control Panel should be placed in Auto any time manual adjustments are made in the region directly in front of the focusing lens. This will prevent burns should the LASER inadvertently fire while exposed skin is in the region where the beam is focused.

4) Follow the 'safing' procedures described in Section II.7.C.(1) and Appendix 3 before any activity is performed in the vicinity of the LASER with the main cabinet cover removed.

APPENDIX 2

CONTROLS AND INDICATORS

MAIN CABINET FRONT PANEL

The 'Dry Air Flowmeter' indicates the flow rate of the dry air through the spark gap. It measures flow in Specified Cubic Feet per Hour (SCFH).

The 'Dry Air Flowmeter Knob' controls the rate of dry air flow. The flow is shut off by turning this knob full clockwise (CW).

The 'Dry Air Pressure Gauge' indicates the pressure with which the dry air flows through the LASER. Pressure is measured in pounds per square inch gauge (psig).

The 'Dry Air Pressure Regulator' controls the dry air pressure. Pressure is reduced to zero by turning the knob full counter-clockwise (CCW). A Philips screw in the center of the knob is available to lock the pressure setting.

The 'Mix Gas Flowmeter', 'Mix Gas Flowmeter Knob', 'Mix Gas Pressure Gauge', and 'Mix Gas Pressure Regulator' perform parallel functions for the mix gas flowing through the LASER.

The 'Main AC Power Switch' applies standard AC, 110 V, power to the LASER.

The 'Main Power Indicator Light' is an amber light which indicates that power (low voltage) is provided to the system. This illuminates any time the Main AC Power Switch is on.

Three 'Fuse Holders' hold the system fuses (Main, Control, and

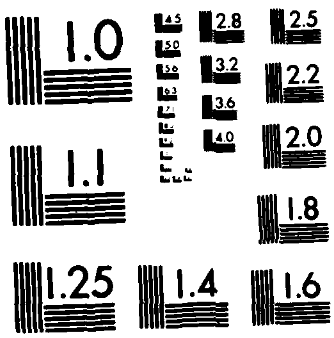
AD-A145 376 DIAGNOSTICS OF IONIZATION IN AIR PRODUCED BY INFRARED RADIATION FROM A PULSE CO2 LASER(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH E S HUTTON 1984 2/2

UNCLASSIFIED AFIT/CI/NR-84-64T F/G 20/5 NL

END

FILMED

DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

High-Voltage). Each will light up when the installed fuse has blown. The rating and blow speed of each fuse is indicated on the front panel above its holder.

The 'Overload Reset Pushbutton' resets the system when the overload circuit is activated. This circuit is activated when overheating occurs or when the main cabinet interlock switch has been opened. Pushing the button has the same effect as cycling the Main AC Power Switch off and back on. See Overload Fault Indicator Light below.

The 'Timer Bypass Pushbutton' causes the thermal timer of the LASER system to be bypassed. This feature is used during system maintenance and should not used for normal daily operation.

REMOTE CONTROL PANEL

The 'Emission Indicator Light' (red) indicates that system AC power has been applied and that the possibility of radiation being emitted exists.

The 'Overload Fault Indicator Light' (red) indicates that overheating has occurred or that the main cabinet interlock switch has been opened. If the main cabinet is closed and this light remains on after depressing the Overload Reset Pushbutton, allow the thermal switch to cool by waiting 10 to 15 minutes with main AC power applied.

The 'Gas Low Fault Indicator Light' (amber) indicates that either the dry air or mix gas pressure is too low. This may be caused by failure to open the supply cylinder valves or by an empty cylinder. Check valves and line pressures and replace cylinder if necessary.

The 'Interlock Open Fault Indicator Light' (white) indicates that the mask cabinet interlock switch is open. This cabinet is not connected in the present setup and the light is therefore inoperative.

The 'Standby Operating Mode Indicator Light' (white) indicates that the high-voltage circuits are safed. This condition is selected by placing the Standby/Operate mode switch in Standby.

The 'Ready Operating Mode Indicator Light' (amber) indicates that the high-voltage circuits are ready to be activated. In the design configuration of the system, charging of the circuits would have been initiated by a 'standby' photocell or microswitch pulse. In the present configuration, the Ready mode has no significance. This mode is selected by placing the Standby/Operate mode switch in Operate and the Auto/Manual On mode switch in Auto.

The 'On Operating Mode Indicator Light' (green) indicates that the high-voltage circuits are active and the mix gas is flowing through the LASER cavity. In the design configuration of the system, the high voltage would be discharged through the spark gap by a pulse from a 'trigger' photocell or microswitch. In the present configuration, the high voltage is discharged by a pulse from the Single Shot Test Pushbutton. In the design configuration, this mode would be selected by placing the mode switches in Operate and Auto and then receiving a pulse from the 'standby' photocell or microswitch. In the present configuration, this mode is selected by placing the mode switches in Operate and Manual On.

The 'Standby/Operate Operating Mode Selector Switch' and the 'Auto/Manual On Operating Mode Selector Switch' are used to select the

modes described above.

The 'Operate/Test Selector Switch' (found on the inside of the Remote Control Panel cover) selects between the operate and test configurations of the system. The 'design configuration' discussed above is selected by placing the switch in the Operate position; the 'present configuration' is selected by placing the switch in the Test position.

The 'Single Shot Test Pushbutton' (found on the inside of the Remote Control Panel cover), when pushed, initiates the pulse which causes the spark gap to break down and, thus, the LASER to fire.

The 'Pulse Counter' (found on the inside of the Remote Control Panel cover) increments each time the LASER is fired.

APPENDIX 3

CHECKLISTS

SAFING THE LASER

[NOTE: This checklist should be run before ANY work is done around the LASER with the cover off.]

1. Ensure that the MAIN AC POWER KEYSWITCH is OFF.
2. WAIT a minimum of 5 MINUTES before any further action.
3. REMOVE LEFT MAIN CABINET COVER (side opposite beam exit hole).
4. REMOVE SMALL GRAY COVER from mid section of main cabinet by CAREFULLY lifting the cover up and out. [DO NOT allow fingers to be placed behind the cover in lifting it off.]
5. REMOVE PLASTIC BAG (if on) FROM SHORTING BAR.
6. With the shorting bar, SHORT THE FOLLOWING points in the given order: [CAUTION: ENSURE GROUND END OF GROUNDING CORD IS ATTACHED TO CABINET BEFORE GROUNDING IS ATTEMPTED.]
    a. Dome nut on spark gap mid-plane terminal. (silver)
    b. Spark gap high voltage terminal. (copper)
    c. Top terminal of main discharge capacitor. (copper)
    d. Bottom terminal of blocking capacitor. (copper)

FIRING THE LASER

1. OPEN VALVE ON TOP OF DRY AIR BOTTLE (yellow) until handle turns no further.
2. CHECK PRESSURE on front guage (line pressure) at 30 PSIG. If not at 30 psig, adjust green knob on side of valve until achieved.
3. OPEN VALVE ON TOP OF MIXED GAS BOTTLE (green) until handle turns no further.
4. CHECK PRESSURE on front guage (line pressure) at 30 PSIG. If not at 30 psig, adjust green knob on side of valve until achieved.
5. Ensure STANDBY/OPERATE KEYSWITCH on remote panel is in STANDBY.
6. Ensure AUTO/MANUAL ON KEYSWITCH on remote panel is in AUTO. [NOTE: Turning this switch to MANUAL ON charges the HIGH VOLTAGE components and allows the mixed gas to flow.]
7. TURN MAIN AC POWER KEYSWITCH ON. (1/8 turn CCW) [ON (amber) light above Main AC Power keyswitch, STANDBY (white) light on remote panel, and EMISSION INDICATOR (red) light on remote panel all come on.]
8. WAIT until warm-up period is over. [This will be indicated by a loud clicking inside the main LASER cabinet and by the Mixed Gas flow and pressure indicators dropping to zero.]
9. ADJUST SPARK GAP PRESSURE to 18 PSIG and FLOW to 0.6 SCFH by the following procedure, if not at those settings after turn on:
   a. Turn flow knob full CW.
   b. Turn pressure knob full CCW. This may require loosening Philips screw first.

c. Open flow knob 1/2 turn CCW. [Pressure and flow go to zero.]

d. Turn pressure knob CW until 18 psig is reached.

e. Turn flow knob slightly CW until 0.6 SCFH is reached.

[Turning flow knob too far CCW will cause it to come off.]

10. TURN STANDBY/OPERATE KEYSWITCH to OPERATE. [STANDBY light goes out, READY (amber) light comes on.]

11. TURN AUTO/MANUAL ON KEYSWITCH to MANUAL ON. [Click is heard from within the main LASER cabinet, READY light goes out, and ON (green) light comes on.]

[NOTE: Turning this switch to MANUAL ON charges the HIGH VOLTAGE components and allows the mixed gas to flow. In order to conserve the mix gas, this keyswitch should be left in the Auto position to the maximum extent possible.]

12. ADJUST MIX PRESSURE to 10 PSIG and FLOW to 3 SCFH by the following procedure, if not at those settings when MANUAL is selected:

a. Turn flow knob full CW.

b. Turn pressure knob full CCW. This may require loosening Philips screw first.

c. Open flow knob 1/2 turn CCW.

d. Turn pressure knob CW until 10 psig is reached.

e. Turn flow knob slightly CW or CCW until 3 SCFH is reached.

[Turning flow knob too far CCW will cause it to come off.]

13. PUT ON EYE SAFETY EQUIPMENT, if not already on.

14. Ensure OPERATE/TEST SWITCH inside cover of remote panel is set to TEST.

15. CLEAR THE FIRING LINE.

16. WHEN READY TO FIRE LASER, PUSH TEST BUTTON inside cover of remote panel.

SHUTTING DOWN LASER

1. TURN AUTO/MANUAL ON KEYSWITCH to AUTO.
2. TURN STANDBY/OPERATE KEYSWITCH to STANDBY.
3. TURN MAIN AC POWER KEYSWITCH 1/8 turn CW to OFF.

   [NOTE: If the main LASER cabinet is to be opened, see 'SAFING THE LASER' checklist.]
4. CLOSE VALVE on top of MIXED GAS BOTTLE.
5. CLOSE VALVE on top of DRY AIR BOTTLE.
6. RETURN LASER KEYS to secure place.

APPENDIX 4

DATA FOR DETERMINATION OF EXTERNAL LENS FOCAL POINT

The following data describes the effects of the LASER beam on heat-sensitive paper. The first entry, produced by the unfocused beam, is the result of five shots; all other entries are each the result of one shot of the LASER. Because the lens tube entends 31 mm beyond the middle of the lens, that distance established the minimum for measurements.

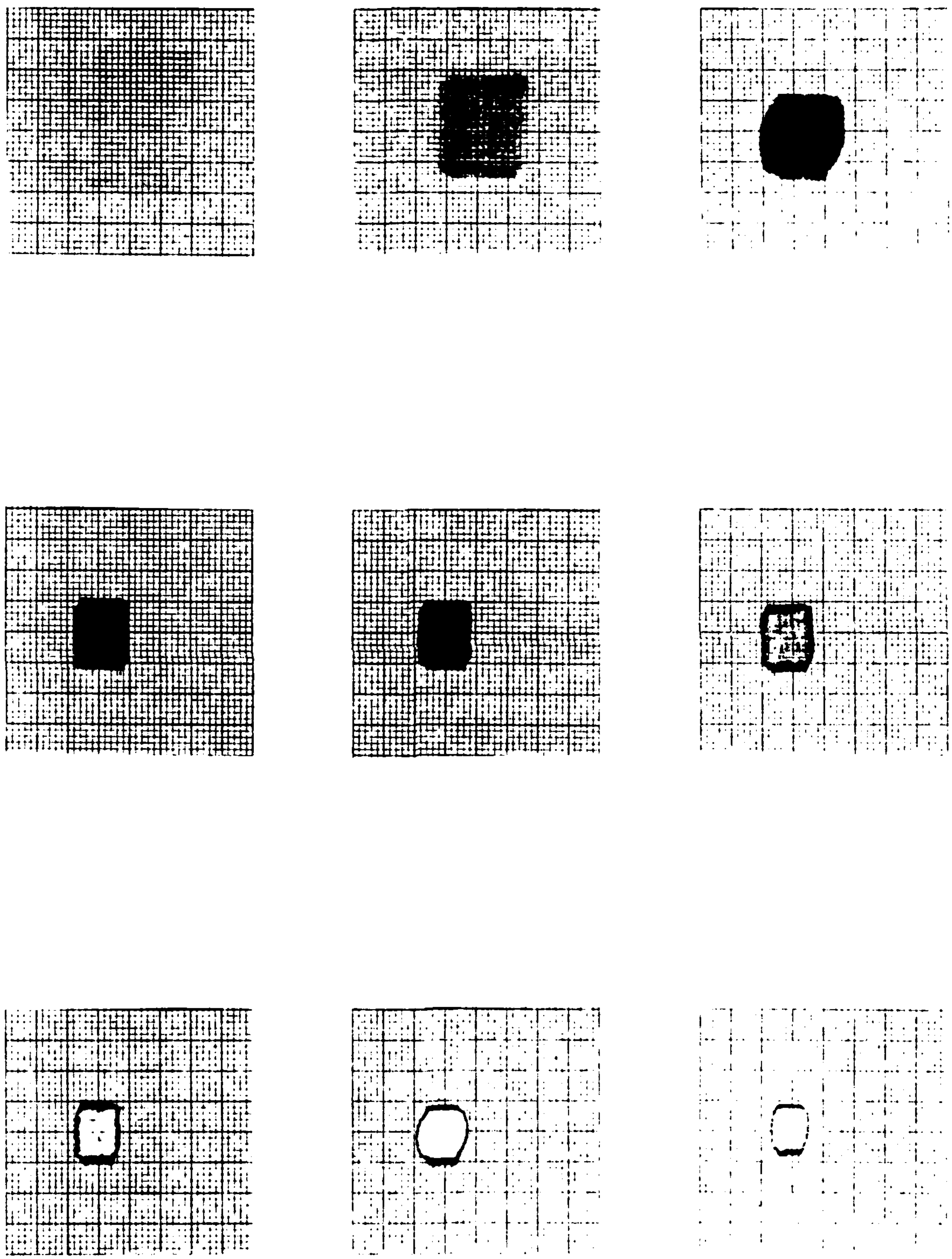
LENS TO PAPER DISTANCE (mm)	VERTICAL SIZE OF IMAGE (mm)	FINAL PAPER CONDITION	ADDITIONAL PHENOMENA
no lens	24	blue	none
31	15	blue	none
50	13	blue	none
54	11	blue	none
58	10 1/2	blue	slight burst of smoke
62	10	burnt white	slight smoke, audible crack
66	8	burnt white	more smoke, audible crack
70	8	burnt white and ruptured	significant smoke, very loud crack
74	8	burnt white and ruptured	significant smoke, very loud crack

APPENDIX 5

FOCAL POINT DETERMINATION IMAGES, SET 1

The following images, recorded on heat-sensitive paper, show the beam size at distances from the focusing lens as indicated below. These images should be viewed in conjunction with the tabular information of Appendix 4.

(a) no lens, 5 shots	(b) 31 mm, 1 shot	(c) 50 mm, 1 shot
(d) 54 mm, 1 shot	(e) 58 mm, 1 shot	(f) 62 mm, 1 shot
(g) 66 mm, 1 shot	(h) 70 mm, 1 shot	(i) 74 mm, 1 shot



APPENDIX 6

FOCAL POINT DETERMINATION IMAGES, SET 2

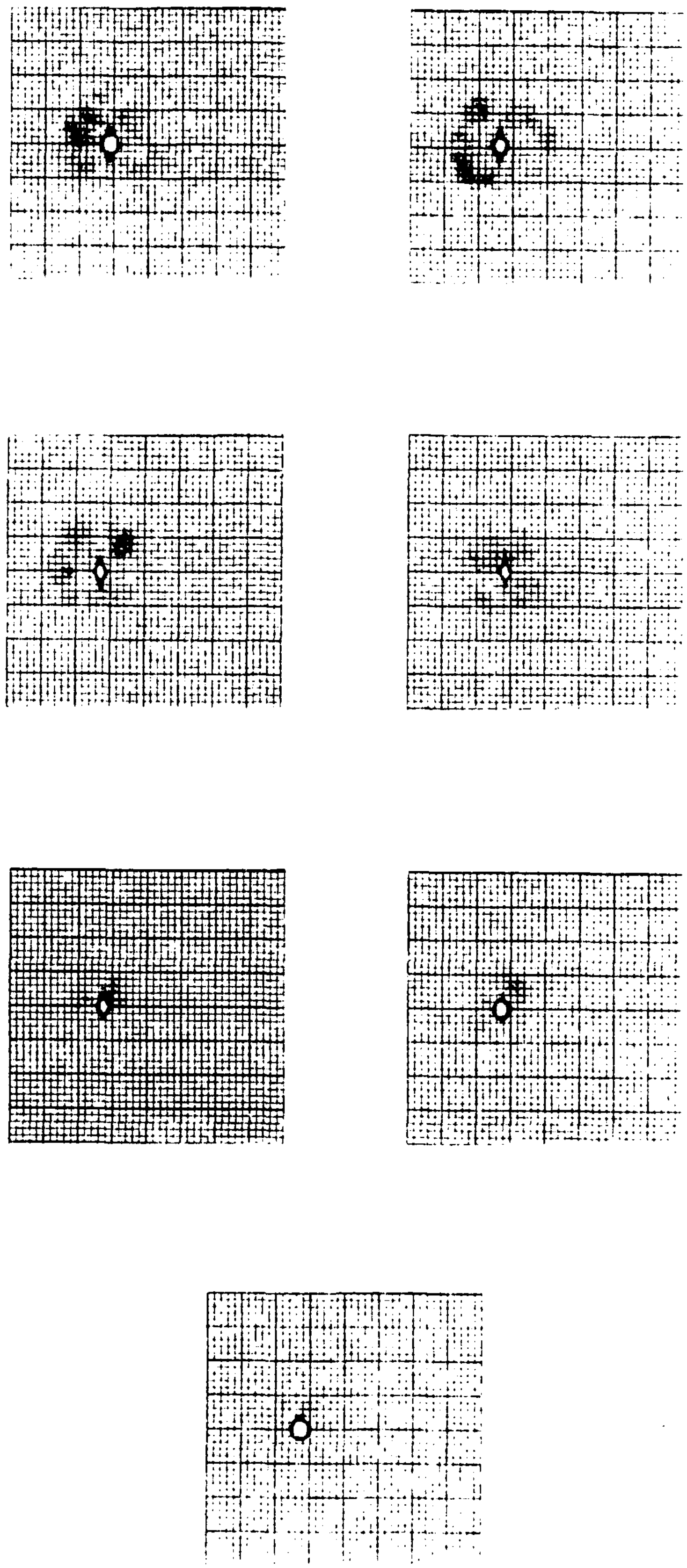
Focal point determination using paper alone proved inadequate because the paper was ruptured by the LASER pulse before the focal point was reached. However, using thin brass sheeting as a backing for the paper, no rupturing occurred and a reliable determination of the focal point was made. The following series of images, on the heat-sensitive paper, shows that the focal point is very close to 96 mm from the lens. Each image was produced by one shot of the LASER. Distances from the lens are indicated below.

(a) 90 mm (b) 92 mm

(c) 94 mm (d) 96 mm

(e) 98 mm (f) 100 mm

(g) 102 mm



BIBLIOGRAPHY

Be 70 A.J. Beaulieu, Appl. Phys. Lett., Vol. 16. 1970.

Bl 56 N. Bloembergen, Phys. Rev., Vol. 104, No. 2. Oct 15, 1956.

Bo 68 Ludwig Boltzmann, Studies on the Equilibrium of the Living Force between Moved Material Points. 1868.

dA 51 A. d'Abro, The Rise of the New Physics. New York: Dover Publications, Inc., 1951.

Du 76 W.W. Duley, CO_2 Lasers, Effects and Applications. New York: Academic Press, 1976.

Ei 17 Albert Einstein, Physik, Vol. 18. Mar 15, 1917.

Ei 74 Robert Eisberg and Robert Resnick, Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles. New York: John Wiley and Sons, 1974.

Ha 74 John E. Harry, Industrial Lasers and their Applications. London: McGraw-Hill Book Company (UK) Limited, 1974.

Ja 61 A. Javan, W.R. Bennett, Jr. and D.R. Herriott, Phys. Rev. Lett., Vol. 6, No. 3. Feb 1, 1961.

Le 64 F. Legay and N. Legay-Sommaire, C.R. Acad. Sci., Vol. 259B. 1964.

Lu 81 Lumonics, Inc., Operator's Instruction Manual for Lasermark System Model 901. Ontario, Canada: Lumonics Inc., 1981.

Ma 60 T.H. Maiman, Nature (London), Vol. 187. Aug 6, 1960.

OS 77 Donald C. O'Shea, W. Russell Callen, and William T. Rhodes, An Introduction to Lasers and their Applications. Reading, MA: Addison-Wesley Publishing Company, 1977.

Pa 64 C.K.N. Patel, Phys. Rev. Lett., Vol. 12. 1964.

Sv 76 Orazio Svelto, Principles of Lasers. New York: Plenum Press, 1976.

Ve 81 Joseph T. Verdeyen, Laser Electronics. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1981.